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UNIVERSITI TEKNOLOGI PETRONAS

NOVEL TECHNIQUES FOR REDUCING COOLING TIME IN POLYMER INJECTION MOULDS USING RAPID TOOLING TECHNOLOGIES

By

KHURRAM ALTAF

The undersigned certify that they have read, and recommend to the Postgraduate Studies Programme for acceptance this thesis for the fulfillment of the requirements for the degree stated.

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PERAK

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DECLARATION OF THESIS

Title of thesis

Novel Techniques for Reducing Cooling Time in Polymer Injection Moulds using Rapid Tooling Technologies

I, KHURRAM ALTAF

hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

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Date: ____________________

DEDICATION

This thesis is dedicated to

My wife and Children

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ABSTRACT

In this research, thermal simulations and injection moulding experiments were performed to compare moulds having cooling channels of circular cross section and those with profiled cross section channels. Studies have been performed on the cooling time reduction in plastic injection moulding by different techniques utilizing thermal simulations and thermal measurements during experiments.

Rapid Tooling (RT) technique, which is a manufacturing technique used to produce injection mould tools in a short period of time, has been applied in this research to fabricate injection moulds having circular and profiled conformal cooling channels. Injection moulding experiments for parts was done with these RT moulds using a vertical injection moulding machine.

Manufacturing of mould patterns was done using 3-dimensional Printer Rapid Prototyping machine which used wax as the build material. Wax patterns were designed, fabricated and used to fabricate the mould cavity and channels. Aluminum Filled Epoxy material was used for the fabrication of mould cavities having circular conformal cooling channels and profiled conformal cooling channels.

As the thermal conductivity of aluminum filled epoxy is much lower than metal moulds, another innovative concept which was embedding a metal insert around the cavity, was also applied for enhancing the heat dissipation. The metal insert was fabricated from aluminum. The concept was tested by fabricating moulds with aluminum inserts. All moulds were tested by injection moulding experiments with embedded thermocouples to measure the temperature of the cavity surface and temperatures were recorded with a data logger. Analysis of the temperature data indicated that the profiled channels had an increased heat dissipation and reduction of cooling time of about 17 percent over the circular channels. With the moulds having aluminum inserts, there was an impressive increase in cooling rate and the cooling time was further reduced by over 50 percent as compared to moulds without inserts.

ABSTRAK

Dalam kajian ini, simulasi haba dan eksperimen telah dijalankan untuk membandingkan acuan yang mempunyai saluran penyejukan keratan rentas bulat dengan idea baru saluran seksyen profil keratan rentas. Kajian telah dilakukan ke atas pengurangan masa penyejukan dalam acuan suntikan plastik dengan teknik yang berbeza menggunakan simulasi haba dan eksperimen.

Peracuanan Rapid (RT) teknik, merupakan satu teknik pembuatan yang digunakan untuk menghasilkan alat acuan suntikan dalam tempoh yang singkat, telah digunakan dalam pembuatan acuan suntikan yang mempunyai saluran penyejukan conformal pekeliling dan profil. Suntikan acuan yang telah dilakukan dengan acuan ini menggunakan suntikan acuan mesin tegak.

Pembuatan acuan bercorak telah dilakukan dengan menggunakan mesin pencetak 3-dimensi Rapid Prototyping yang menggunakan lilin sebagai bahan utama. Corak direka, dicetak dan digunakan untuk rongga acuan dan saluran. “Aluminium filled epoxy” telah digunakan untuk fabrikasi kaviti acuan yang mempunyai saluran penyejukan berbentuk bulat dan profil saluran penyejukan conformal.

Kekonduksian haba bagi “Aluminium filled epoxy” adalah lebih kurang daripada logam acuan, satu lagi konsep yang inovatif dan baru yang menerapkan memasukkan logam di seluruh rongga, telah digunakan untuk meningkatkan pelupusan haba. Memasukkan logam inserts telah yang direka daripada aluminium. Konsep ini telah diuji dengan pembuatan acuan dengan aluminium inserts. Semua acuan yang telah diuji melalui suntikan acuan ujian dengan thermocouples untuk mengukur suhu permukaan rongga dan suhu yang direkodkan dengan Logger data. Analisis data suhu menunjukkan bahawa saluran yang dipaparkan mempunyai pelesapan haba meningkat dan pengurangan masa penyejukan kira-kira 17 peratus berbanding saluran bulat. Dengan acuan yang mempunyai aluminium inserts, terdapat peningkatan yang

memberangsangkan dalam kadar penyejukan dan masa penyejukan terus dikurangkan sebanyak lebih 50 peratus berbanding dengan acuan tanpa inserts.

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LIST OF ABBREVIATIONS

3DP	3 Dimensional Printing
ACES	Accurate Clear Epoxy Solid
CAD	Computer Aided Design
CCCC	Circular Conformal Cooling Channels
CAE	Computer-Aided Engineering
CNC	Computerized Numerical Control
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
EDM	Electrical discharge machining
FDM	Fused Deposition Modelling
IM	Injection Moulding
LENS	Laser Engineered Net Shaping
PCCC	Profiled Conformal Cooling Channels
RP	Rapid Prototyping
RT	Rapid Tooling
SLA	Stereolithography
SLS	Selective Laser Sintering
SLM	Selective Laser Melting
TC	Thermocouple
VIM	Vertical Injection Moulding
VRCCC	Variable Radius Conformal Cooling Channel

NOMENCLATURE

Symbol	Description
A	Area
c_p	Specific heat
D	Diameter
D_H	Hydraulic diameter
h	Convective Heat Transfer Coefficient
k	Thermal conductivity
Pr	Prandtl's Number
q	Heat flow
R	Thermal resistance
Re	Reynold's number
S	Shape factor
T	Temperature ^{o}C
t	Elapsed Time
Δt	Time interval
V	Velocity

Greek symbols

ρ	Density of water
μ	Dynamic Viscosity of water

CHAPTER 1

INTRODUCTION

1.1 Overview

These days, a vast variety of plastic products is available. One of the most common methods of shaping polymers is a process called injection moulding which is a big business in the worldwide plastic industry [1]. In Injection moulding, the process cycle time is a vital factor affecting the productivity of the process. The process cycle time relies significantly on the cooling time of the plastic part which is facilitated by the cooling channels in the injection mould. Conventional cooling channels are traditionally made of straight drilled holes in the mould, which have restrictions in terms of geometric complexity as well as cooling fluid flow within the injection mould. Over the years, conformal cooling techniques have been introduced as an effective alternative to conventional cooling [2].

The benefit of the injection moulding process is that production of parts with complicated geometries can be accomplished at high production rates. However, manufacturing of moulds with complex geometries tend to be more challenging. The injection moulds are normally manufactured using conventional machining techniques like EDM, wirecut EDM, CNC milling etc, which can take quite a long time. This in turn can raise tool costs exponentially with the level of difficulty and therefore mould cost is a major factor in the overall product costing. If only a few injection moulding parts are required for an application, then Rapid Tooling (RT) technologies could be a feasible way for fabricating moulds.

RT technology is an alternative method to fabricate injection moulds using layered manufacturing technologies. RT is a process that either indirectly utilizes a rapid prototype as a tooling pattern for the purposes of moulding production or it can directly produce a mould with a rapid prototyping system.

Manufacturing of aluminium filled epoxy moulds is reasonably quicker in comparison with machined moulds. It is a relatively inexpensive and quick way to create prototype and production tools but has the limitation of low volume production capacity.

1.2 Injection Moulding (IM) Process

Injection moulding is an important process of the plastics-forming industry with a huge impact on business worldwide. It is one of the most common methods to convert raw polymer to an end product of practical use. This process is normally used for thermoplastic materials which may be sequentially melted, reshaped and cooled. Practically every manufacturing item in the modern world, from automotive parts to food packaging involve the use of injection moulding components. This flexible process allows us to make high quality complex components on a fully mechanized basis at high speed that has changed the face of manufacturing technology over the last several decades. A typical injection moulding machine is shown in Figure 1.1.

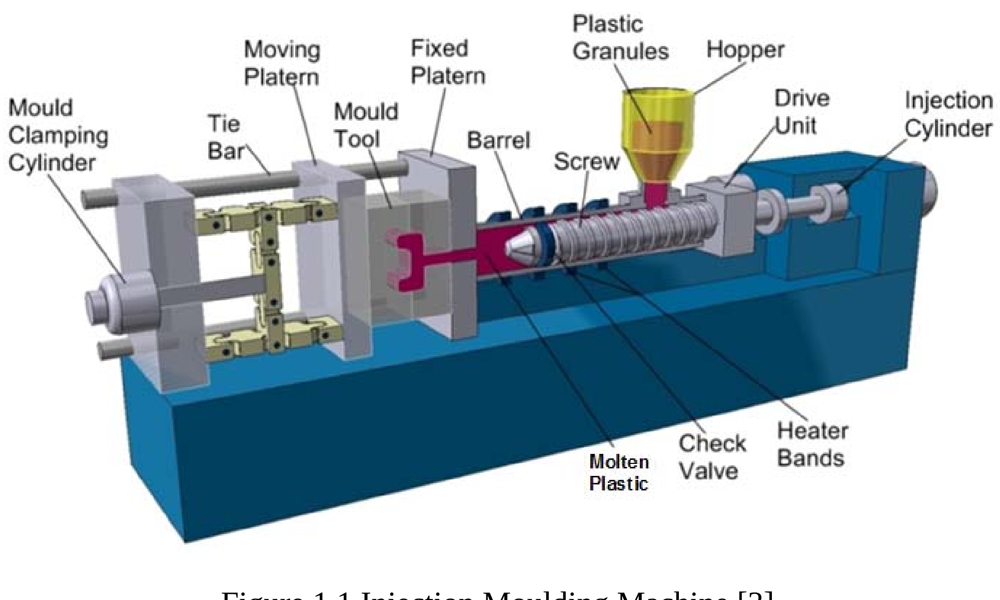

Figure 1.1 Injection Moulding Machine [3]

Injection moulding (IM) is a repeated manufacturing process used to convert raw material, usually polymers, into different types of products. The term "injection moulding" refers to a general process where the molten polymers are injected into a mould cavity and then allowed to solidify to obtain the final shape.

The injection moulding process is the most common process for polymer manufacturing and has the following major advantages:

- High production rate
- Comparatively low labour cost per unit
- High quality parts with various shapes, colours and finishes
- Low material wastage as runners and gates can be recycled
- Close dimensional tolerances
- Automated process

1.2.1 Injection Moulding Cycle

IM process consists of the following steps which are successively repeated.

1. Injection of material
2. Packing and holding
3. Cooling of part
4. Ejection of part

In the injection stage, the melted polymer is injected into a cavity formed by two halves of the mould. After the cavity has been completely filled, additional melted material is packed into the cavity at high pressure in order to compensate for the shrinkage of the part in cooling. In the cooling stage, the part is solidified to the point where no significant deformation will occur on the part at ejection. The mould is opened and the part is ejected from the mould. The moulding machine then starts the next process cycle.

As seen from Figure 1.2, nearly 50 percent of the cycle time elapses in the cooling of the part to that temperature at which it can be ejected from the mould. If the cooling time is reduced, it will have a direct impact on the moulding cycle resulting in a reduction of cycle time and an increase in productivity. For this reason, much research done on the injection moulding technique is on the reduction of cooling times for Injection Moulding.

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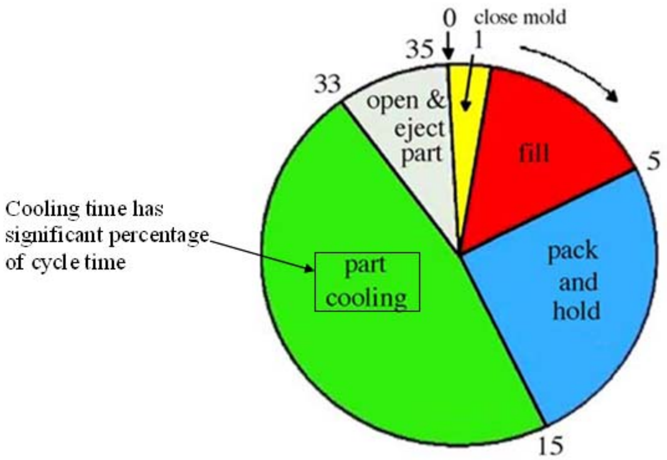


Figure 1.2 Cycle time in injection moulding [4]

1.2.2 Cooling System in Injection Mould Manufacturing

The mould is the most vital part of the IM machine. It is a controllable, complex, and expensive device. If the mould is not properly designed, operated, handled, and maintained, its operation will be costly and inefficient. Under pressure the hot melted polymer moves quickly into the mould cavities. The moulding of thermoplastics requires cooling of the part and mould which is achieved with the circulation of water through the mould for the removal of heat from the moulded part. Cooling channels within the mould, which are manufactured by drilling holes around the cavity by conventional machining techniques, carry the cooling medium. To prevent the formation of voids in the product, air in the cavity or cavities is expelled during the process of injection into the mould [1].

1.2.3 Conformal cooling

Process cycle time is the key factor in Injection Moulding affecting the productivity of the process. The cycle time in injection moulding process depends on the cooling time of the moulded part, which is provided by the cooling channels in the injection mould. Conventional cooling channels fabricated with straight drilled holes in the mould have geometric and cooling fluid mobility limitations. To overcome these problems, the technique of conformal cooling is being introduced as an alternative to conventional cooling [2].

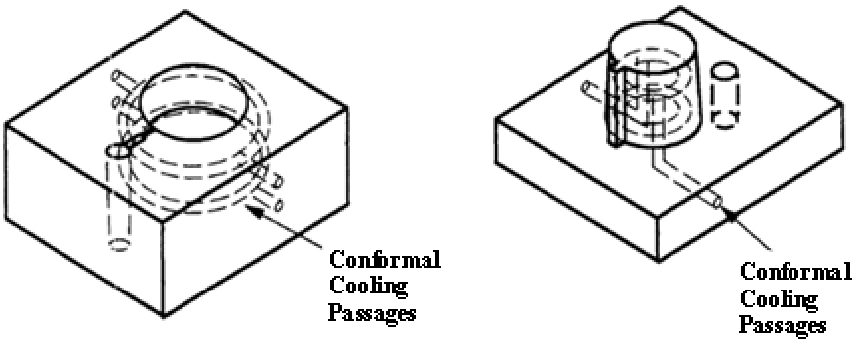
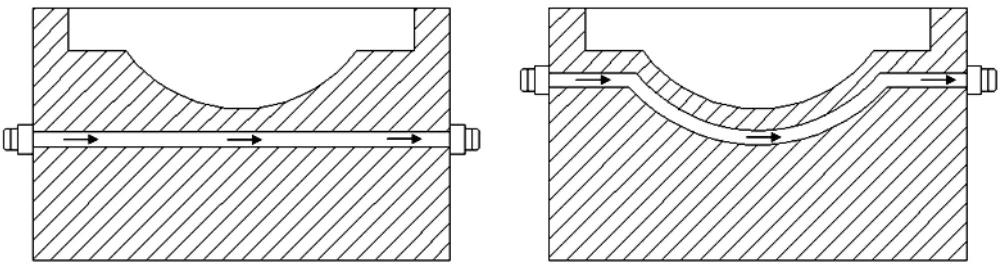


Figure 1.3 Conformal Cooling Passages. [5]

The development of Solid Freeform Fabrication (SFF) techniques has offered new degrees of liberty to injection mould manufacturers. The SFF processes add material resulting in the construction of 3D objects by incrementally depositing cross sectional layers of random complex shapes converted from CAD solid models. The ability to manufacture 3D objects with complex features makes these techniques tremendously valuable for fabricating parts and tools that cannot be made by other methods. An example of its application is to fabricate intricate cooling channels within an injection mould so as to improve the consistency of cooling. The technique of conformal cooling channels can be seen in Figure 1.3. The conventional and conformal cooling channels are shown in Figure 1.4.



(a) Conventional (b) Conformal

Figure 1.4 Cooling Channel Geometries

1.3 Rapid Prototyping (RP)

Rapid Prototyping (RP) is a technique that makes a three-dimensional part that a person in product development can physically hold and feel as compared to seeing a computer drawing of one. These RP parts can also be used for design validation and measurement. Depending upon the customer's request, functional tests can be performed on such RP parts. An interesting proverb in RP that is derived from an old saying "a picture is worth a thousand words" is that a Rapid Prototype is worth a thousand pictures or drawings.

RP technologies can build physical parts from three dimensional (3D) Computer Aided Design (CAD) data. The 3D CAD file is divided into thin cross sections or layers by the RP system software. These layers are then progressively deposited with either solid, liquid or powder based materials on top of each other to make a solid part. All RP systems work on these same principles.

Rapid prototyping (RP) is a basic jargon for a range of technologies that that are used for producing actual three dimensional objects directly from CAD data without the need for conventional tools or a skilled operator for the machine. These techniques are distinctive in a way that they add material in layers to build parts. These technologies are also known by various other terms such as Additive Fabrication, Three Dimensional Printing (3DP), Solid Freeform Fabrication (SFF) and Layered Manufacturing (LM). The additive technologies offered these days have benefits in many applications compared to conventional material removal manufacturing methods such as turning or milling. Objects with any degree of geometric intricacy can be produced without the need for intricate system setup or final assembly. RP systems reduce the building of intricate objects to a convenient, simple, and relatively fast process [6].

Some of the RP systems commercially available are

- Stereolithography, SLA
- Selective Laser Sintering, SLS
- Fused Deposition Modelling, FDM
- 3 Dimensional Printing, 3DP

- Selective Laser Melting, SLM
- Direct Metal Laser Sintering, DMLS
- Electron Beam Melting, EBM

Rapid Prototyping Processes can also be categorized according to the material used

- Liquid based Materials like SLA.
- Solid based materials like FDM.
- Powder based materials like SLS, DMLS, 3DP.

1.4 Rapid Tooling (RT)

The technologies based on layered manufacturing (LM) techniques are broadening their areas of application, from the fabrication of functional prototypes to the fabrication of tools and moulds for secondary applications like injection moulding. In particular, additive fabrication applied to the production of moulds, dies and electrodes, directly from digital data, is defined as rapid tooling (RT) [7].

The need for tight tolerances and faster speeds has created the need for innovation in the RP industry. This in turn has developed researches in the technologies of quickly producing working tools for production. RT is a technique with which tools for injection moulding or die casting processes can be manufactured quickly and economically. Another definition of Rapid Tooling is the application of RP techniques for the fabrication of customized moulds, dies, and tools used to manufacture parts. RT either uses a pattern created with an RP system or directly involves other RP techniques in the creation of the tool. For this reason, RT is categorized into direct and indirect techniques.

RT techniques were developed which use RP technologies to initiate the mould making process. RT can produce mould tooling in two ways: (1) directly, by creating a mould from a CAD file and using a RP machine that uses stronger materials (2) indirectly, by forming a mould over an existing part used as a pattern. These RT techniques can reduce mould making time substantially [8]. The RT technologies used by the industry are given below.

- RTV Silicone Rubber Moulds
- Reaction Injection Moulding (RIM)
- Spin-Casting
- Spray Metal Tooling
- Cast Resin Tooling
- Electroforming
- Investment Cast Tooling
- Direct AIM tooling
- SLS Rapid Steel
- Direct Metal Laser Sintering
- Laser Engineered Net Shaping (LENS)

The RT technique used for the current research was Cast Resin Tooling.

1.5 Problem Statement

The limitation of conventional injection moulds with straight cooling channels is uneven heat distribution. Although conformal cooling channels has considerably enhanced the heat dissipation and distribution in injection moulds, there is still more room for further improvement. From the study of previous literature, it was observed that several investigations have been conducted in cooling systems in injection moulds with the aid of different RT technologies. Various researchers have studied mould cooling with different approaches. It was also seen in the literature that with the use of RT techniques, manufacturing and thermal performance of injection mould had improved.

In cooling channels with circular cross section, the distance between the edges of cooling channel and the edges of cavity in the mould cannot be constant due to geometric constraints. This can give problem of not having even heat dissipation and higher cooling times. Hence, the work in the research will be to solve this problem with implementing the technique of Profiled Conformal Cooling Channels. The material used to fabricate RT moulds is aluminium powder filled epoxy which has quite a low thermal conductivity. The problem of low thermal conductivity of epoxy will be solved with the embedding of good conducting metal inserts in the moulds.

1.6 Aims and Objectives

The main objective of this research is to enhance mould cooling rate and even heat dissipation with the use of Profiled Conformal Cooling Channels (PCCC) and Conducting Metal Inserts (CMI) in an Injection Mould, fabricated with aluminium filled epoxy as the build material using Rapid Tooling techniques. It is hypothesised that combination of PCCC and CMI would be able to further decrease mould cooling time and reducing the overall injection moulding cycle time.

Therefore, the objective of this research is to further enhance the cooling time and more even heat distribution in injection mould tools fabricated with epoxy. This is done by the following steps.

i. To design and fabricate injection moulds with aluminium filled epoxy material of various cooling channel configurations for injection moulding
ii. To analyse the cooling performance and thermal distributions of the aluminium filled epoxy moulds without and with conducting metal inserts through experimental works and CAE/FEM approaches.
iii. To perform comparative evaluation on the aluminium filled epoxy moulds.

1.7 Research Methodology

In the current research, two techniques have been proposed to further reduce the cooling time in plastic injection moulds. The first technique is the use of a new channel cross section which follows the profile of the cavity and hence called as a Profiled Conformal Cooling Channel or PCCC. The second technique used to further enhance the cooling time in the moulds made with epoxy is to embed aluminium inserts between the cavity and the cooling channel. This can further reduce the cooling time as aluminium is a very good conductor of heat and hence this technique will further decrease the cooling time in the epoxy moulds. These techniques will be confirmed with thermal analysis and actual injection moulding experiments. The steps for the methodology are:

- Design calculations for circular and profiled channels.
- Design of moulds having circular and profiled cooling channels.
- Design of moulds having circular and profiled cooling channels with aluminium inserts.
- Thermal analysis of the moulds with the above features, to check the effectiveness of moulds cooling time reduction.
- Fabrication of RP patterns.
- Fabrication of moulds with epoxy material.
- Injection moulding experiments for the confirmation of the hypothesis and the analytical results.

Some of the limitations for the injection moulds manufactured with epoxy are that they can be used for limited sizes and for low volume production (up to 100 parts).

1.8 Thesis Organization

The thesis commences with an introductory chapter which discusses the process of injection moulding, mould cooling and a general description of the technologies of Rapid Prototyping and Rapid Tooling. In chapter 2 and extensive review of the literature on the foregoing topics has been provided along with different approaches to mould cooling time reduction. Chapter 3 contains a comprehensive account of the research methodology. In chapter 4, the experiments and numerical results are discussed. The major conclusions of the thesis and suggestion for future work are described in chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a detailed and in depth review of RP and RT technologies. The review is mostly about the application aspects of these technologies. In the current chapter, the technologies of Rapid Prototyping (RP), Rapid Tooling (RT) and Injection Mould manufacturing with Rapid tooling are dealt with, and the emphasis is on the cooling system within the mould. Tool or Tooling is a term used to describe fabricated equipment used for manufacturing of parts or components. The part material can be polymer or metal depending upon the process. For polymers, injection moulding process is utilized and for metallic parts pressure die casting process is used. In the current research, the main importance is given to the Injection Moulding Process and mould manufacturing using RT techniques with circular and profiled conformal cooling channels and moulds with conducting metal inserts.

2.2 Rapid Prototyping Technologies

Rapid Prototyping (RP) is the term given to a range of technologies that can produce physical three dimensional parts directly from computer aided design (CAD) data. These techniques are distinctive in that they deposit solid or liquid based materials in layers to fabricate objects. These technologies are also known as:

- Additive Fabrication,
- Three dimensional printing,
- Solid freeform fabrication,
- Layered manufacturing.

RP techniques have many advantages over conventional fabrication and machining methods like turning or milling which are subtractive in nature as these technologies remove material to get the desired shape of the object.

2.2.1 Stereolithography (SLA)

The first commercial RP technology was Stereolithography or SLA. SLA was invented in 1984 by Hull. He patented the SLA technology in 1986 under U.S patent No. 4,575,330 [9]. SLA is one of the oldest RP processes. SLA can make objects with intricate geometry with a surface finish comparable to that of machined parts. SLA parts are often used as masters to produce silicone moulds for vacuum or Room Temperature Vulcanizing (RTV) moulding. They are also used as disposable patterns in the investment casting process. SLA parts have the advantage of good surface finish and accuracy but the parts need support structures that must be detached in a finishing operation and also SLA resins are harmful and need careful handling [10].

In SLA process, a moveable platform is located primarily at a position just under the surface of a container containing liquid photopolymer resin. This material has the property that when a laser beam strikes it, it cures and changes from a liquid to solid. The machine chamber is sealed to avoid inhaling the vapours from the resin. A laser beam is moved over the surface of the liquid photopolymer to sketch the geometry of the layer of the part to be built. This causes the liquid to cure in areas where the laser strikes. The laser beam is moved in the X and Y directions by a scanner system controlled by fast and highly precise motors which steer mirrors guided by information from the CAD data [11]. The Stereolithography process is shown in Figure 2.1.

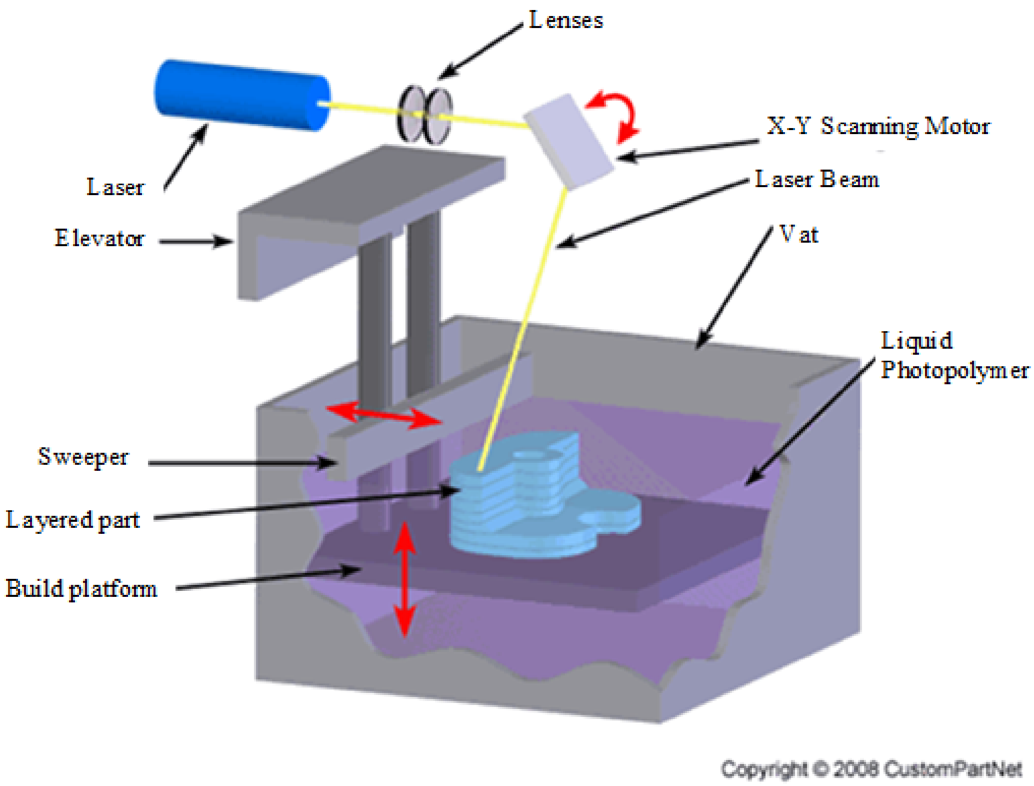


Figure 2.1 Stereolithography Process [11]

After the layer is completed, the table is lowered into the container to an equal distance as the layer thickness. As the resin is highly viscous, for speeding the process of recoating fresh material, a sharp edge moves on the surface of the resin to smooth it. This system is driven either mechanically or with a hydraulic system. The tracing and recoat steps continue until the object is complete and rests on the build platform at the bottom of the container.

Some objects have overhangs or undercuts that need supports during the building process. After completing the process, the object is lifted from the container and excess resin is drained and then cleaned manually from the surfaces. The parts can be given a final cure inside a post-curing apparatus [12].

2.2.2 Selective Laser Sintering (SLS)

After the introduction of SLA technology, many other RP techniques emerged with the same basic principle but with other materials for building parts. One such technology is known as Selective Laser Sintering or SLS which uses powder based materials and a laser to fuse or sinter the powder particles to form layers. Metallic powder can be used in the SLS process to form metal parts. The process of SLS was invented and patented by Deckard at the University of Texas at Austin in 1991 [13]. Later on, it was commercialized by the DTM Corporation. SLS process has an advantage as compared to other techniques of additive manufacturing in that parts can be produced from a comparatively broad range of commercially obtainable materials in powder form. These include polymer materials such as polystyrene or nylon or metal powders including steel, titanium, and composites.

In the Selective Laser Sintering (SLS) technique, parts are created by fusing or sintering powdered thermoplastic or metallic materials with the heat from a laser beam. The object is completed by repeating the process and fusing thin powder layers using a laser. This additive manufacturing cycle produces parts which increase in size until they reach the required dimensions.

The advantage of SLS technique is that parts have material properties similar to the injection moulded parts. SLS also has the capability to make metal prototype parts using metal powder materials. SLS can also build parts with rubber like properties, such as bellows and gaskets, using elastomeric materials. Another benefit is that there is very little post processing necessary after the sintering is finished [14]. The SLS technique is shown in Figure 2.2.

A study by Kruth et al. [15] was on the SLS materials. They found that for many materials, powders that show low fusion or sintering properties can be laser sintered by adding a disposable binder material to the basic powder. After sintering the complete part, the binder can be removed from the so called green part in a furnace. The use of binders can enlarge the particles of laser sintered materials. However, the variety of materials that can be laser sintered without sacrificial binder is quite large as compared to other RP methods. No supports are needed for SLS as the loose powder supports overhangs and undercuts.

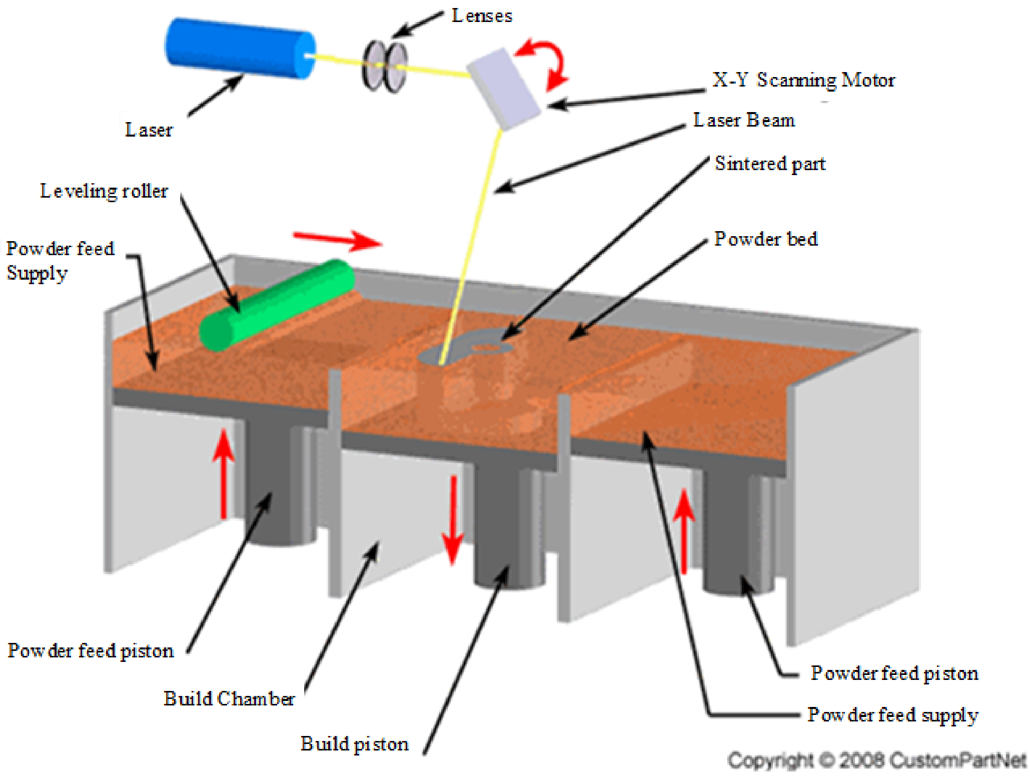


Figure 2.2 Selective Laser Sintering RP Process [16]

Agarwala [17] et al. did an experimental research on the post processing of SLS parts to improve the structural integrity of the parts. They presented their results showing the effect of post-processing during the liquid phase and sintering temperature on material properties. The process of hot isostatic pressing was also described in their work, which discusses its use in the SLS metal parts. The outcome obtained from using this technique showed that it is appropriate for getting almost full-density parts.

2.2.3 Fused Deposition Modelling (FDM)

The Fused Deposition Modelling or FDM technology was invented by Scott Crump in the late 1980s and was commercialized in 1990. In the FDM technology, a polymer wire is unrolled from a coil and is sent to an extrusion nozzle. The nozzle is at an elevated temperature to melt the polymer. This nozzle is attached to a mechanical system which moves in both horizontal and vertical directions. When the nozzle moves over the table in the required geometry, it deposits a thin bead of extruded plastic to make each layer. The plastic cures and hardens instantly after extrusion from the nozzle and bonds to the layer below. The complete system is enclosed within a closed chamber which is maintained at a temperature just below the melting temperature of the polymer [18].

Numerous engineering thermoplastic materials are available like ABS, polycarbonate and polyphenylsulfone which further expands the capability of the technique in terms of temperature and strength ranges. Support structures are deposited for suspended geometries and are removed afterwards by either breaking them or dissolving in a water-based solution. The finish of FDM parts has been greatly enhanced over the years [18]. The FDM process can be seen in Figure 2.3.

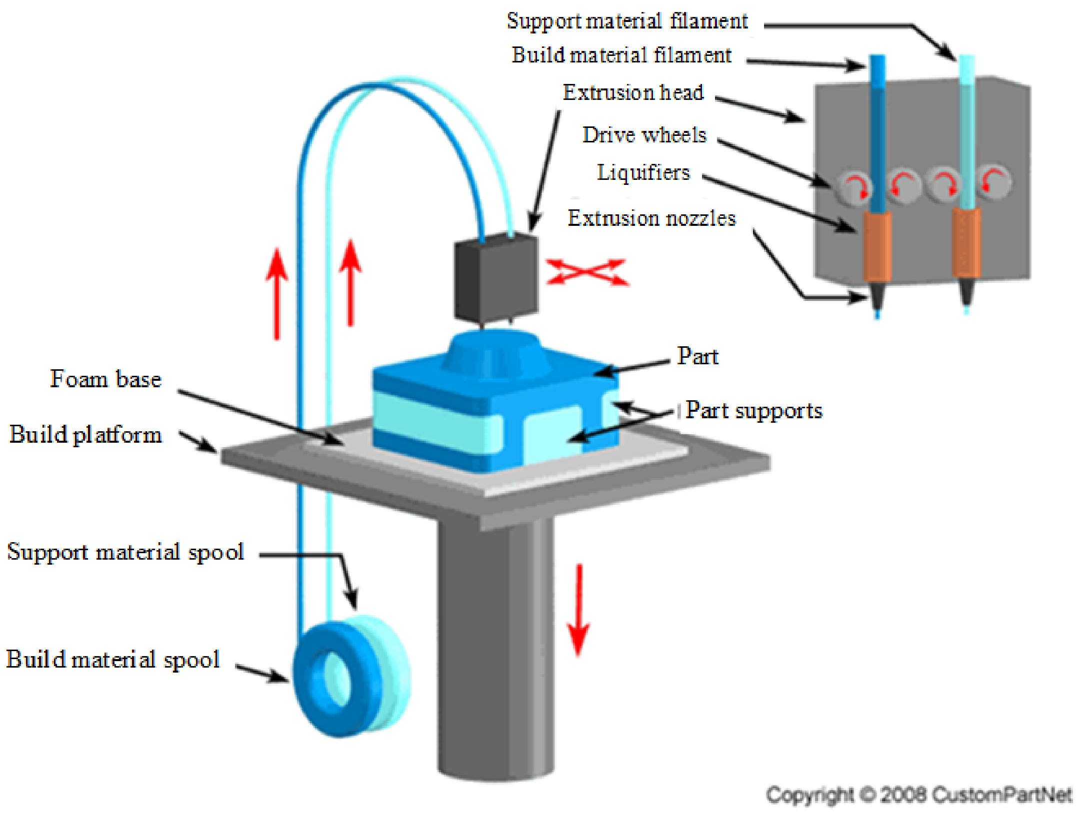


Figure 2.3 Fused Deposition Modelling Process [19]

A study by Masood [20] was on the process of Fused Deposition Modelling (FDM) RP process. In the study it was described that fused deposition offers the prospects of fabricating parts precisely in a wide range of materials safely and quickly. With the use of this technology, the designer is often faced with a host of contradictory options including achieving desired accuracy, optimizing building time and cost, and getting functionality requirements. The study presented a method for resolving these problems through the development of an intelligent RP system integrating scattered blackboard techniques with different knowledge-based and feature-based design methods.

2.2.4 Three Dimensional Printing (3DP)

3DP process is comparable to the SLS technique, the difference being that in place of laser, an inkjet head is used to spray a liquid binder on the top layer of a bed of powder material. The particles of the powder become adhered in the areas where the adhesive is sprayed. Once a layer is done, the piston with the powder bed moves down by the thickness of a layer. Just like SLS, the material supply system is similar in function to the build cylinder. The process repeats until the entire part is completed and buried within the powder block. After the part is built, the bed is elevated and the spare powder is removed with a brush, leaving a so called green part. To evade the risk of damage to the part, they are infiltrated with a hardener before they can be handled [21]. The Three Dimensional Printing technique is shown in Figure 2.4.

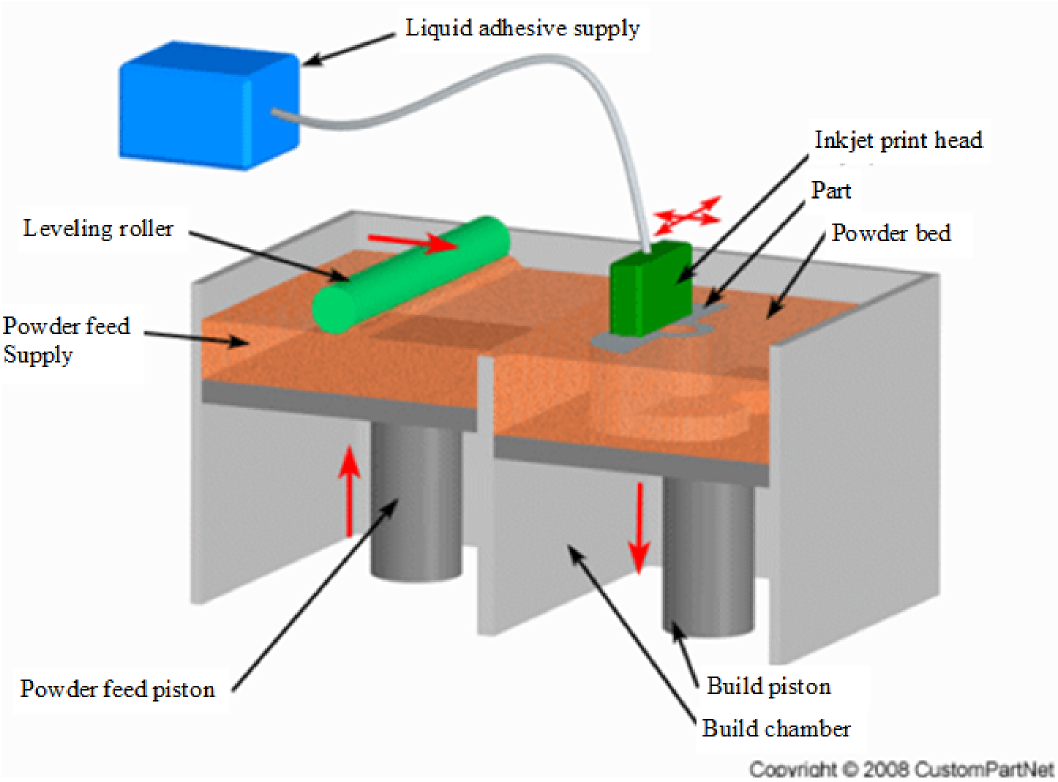


Figure 2.4 Three Dimensional Printing Process [21]

2.2.5 Thermojet 3D printing process

3D systems introduced their 3D printer, the Thermojet in 1999. The Thermojet was intended as a concept modeller. The purpose of a concept modeller is mainly to generate a 3D part in the fastest possible time for design review. The process of the Thermojet is simple and fully automated. It consists of the following steps.

1. Thermojet uses the system software to input STL files from the CAD software. The software also helps users to auto-position the parts to be built so as to optimize building space and time. After all details have been finalized, the data is placed in a queue, ready for Thermojet to build the model.
2. During the build process, the print head is positioned above the platform. The head begins building the first layer by depositing materials as it moves in the X-direction. As the machine's print head contains a total of 352 heads and measures 200 mm across, it is able to deposit material fast and efficiently.
3. With a print head measuring 200 mm across, Thermojet is able to build a model with a width of up to 200 mm a single pass. If the model's width is greater than

200 mm then the platform is repositioned (Y-axis) to continue building in the X-direction until the entire layer is completed.

After one layer is done the platform is lowered and the building of the next layer begins in the same manner as described in Steps 2 and 3 [22].

The Thermojet 3D Printer is shown in Figure 2.5.

Figure 2.5 Thermojet 3 Dimensional Printer

For the current research, Thermojet 3D printer was used for the rapid prototyping of the patterns for cooling channels and cavity. Thermojet uses a wax based material for producing the parts. This material is easily melted and as the fabrication technique for the moulds used in the research is through melting out of the patterns so the Thermojet is a suitable choice for the current research.

2.3 STL File Format

For sending a 3D file to be built in a RP system, the CAD file needs to be converted into an STL file format. A *StL* (StereoLithography) file is a triangular depiction of a 3-dimensional surface geometry. This file format is accepted by many other CAD solid modelling software and is widely adopted for RP and computer-aided manufacturing. In a STL file only the surface geometry of a 3D object is described without any depiction of colour, texture or other common CAD model attributes. The STL format specifies both ASCII and binary representations. Binary files are more common, since they are more compact [23].

2.4 Stair-stepping Effect

All RP systems build parts in layers. Parts having straight edges and sides can be built without many problems, but parts having curved and angular faces will be having rough surfaces due to a phenomenon known as Stair-stepping Effect in RP technology (Figure 2.6). This is because of the fact that the layers have a finite thickness which causes stair-stepping effect. Those RP processes that build the thinnest layers have less stair-stepping than others, but this will be always visible. SLA produces thin layers, and this feature is mainly used to make small parts in the several millimetres or smaller range.

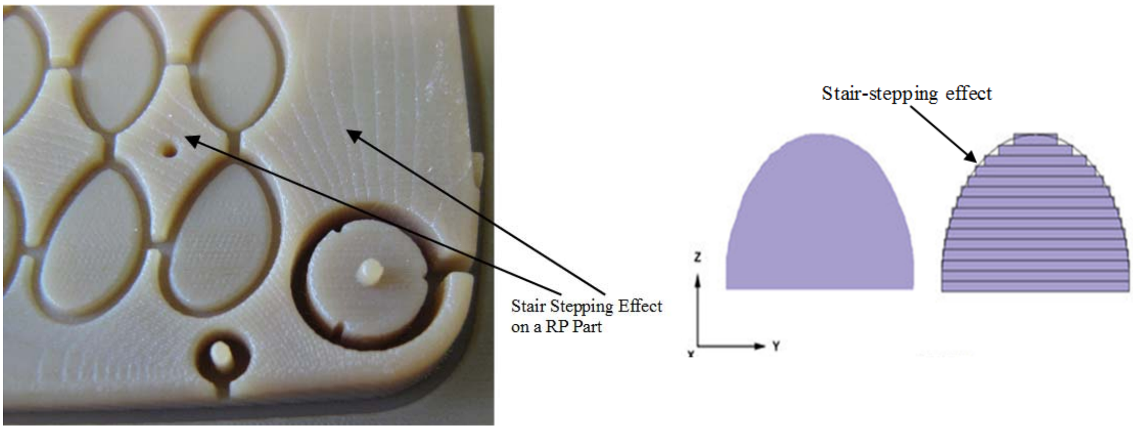


Figure 2.6 Stair-stepping Effect

2.5 Post-processing of RP parts

Many of RP generated parts must undergo some finishing operations before they can be utilized in a secondary process. No RP technology today delivers surface finishes that are suitable for processes such as injection moulding tools. Removal of the stair-stepping effect inbuilt in the process is necessary before parts can be used for a secondary manufacturing operation.

The accuracy of most secondary processes is usually restricted by the accuracy of the pattern after finishing. RP patterns are best for applications with just a few vital dimensions but if there are many tight tolerances required, it is usually still fast and more economical to use CNC machining processes.

Rapid prototyping (RP) technology can fabricate any three dimensional actual model despite its geometric intricacy using the layered manufacturing (LM) process. In general, the surface quality of a raw SLA-generated part is inadequate for industrial purposes because of the stair stepping effect created by the layer manufacturing process. Despite the increased number of applications for SLA parts, this side effect limits their uses. In order to improve their surface finish, additional post processing, such as traditional grinding, is required, but post processing is time consuming and can reduce the geometric accuracy of a part. Therefore, a study by Ahn and Lee [24] proposed a post-machining technology combining coating and grinding processes to improve the surface quality of SLA parts. Paraffin wax and pulp were used as the coating and grinding materials. By grinding the coating wax only up to the boundary of the part, the surface smoothness could be improved without damaging the surface.

2.6 Rapid Tooling Technologies

For the fabrication of tools and dies, Rapid tooling (RT) is a technology of either indirectly using a rapid prototype as a pattern for the purposes of moulding production materials (thermoplastics), or directly fabricating a tool with a rapid prototyping system. These are known as direct and indirect RT technologies. The major problems in the development of injection moulding tools include the growth in material technology and the improvements in tool design methodology. It is vital to develop fast methods to produce tools for injection moulded prototype parts or mass-produced parts. Manufacturing of injection moulds with aluminium filled epoxy is reasonably fast in contrast with machined moulds. It is a comparatively inexpensive and quick way to create prototype and production tools. If the moulds are designed properly, they can endure the injection or compression pressures with the use of aluminium frames. However, because of the poor thermal conductivity of the material, the process cycle time is higher due to longer cooling times [25].

2.6.1 Direct Fabrication Processes

Specific RP methods have been formulated to meet precise application and material demands for moulding and casting. These may be forms of basic RP techniques, such as SLA or SLS, or there might be unique RP techniques developed for an exact application. Research is being done on a huge number of technologies, but only a few are commercially available at present.

2.6.2 Indirect or Secondary Processes

Even though RP materials continue to advance and develop, their comparatively small number with a vast range of manufacturing applications means that there will always be a need to convert parts fabricated from one material into another material. Therefore, various material transfer technologies have been developed. Usually a part fabricated by the RP system is utilized as a pattern or model in these techniques. For the case of the direct fabrication processes, there are many secondary processes either available or in the development stages [26].

2.6.3 Indirect Processes that Use RP Patterns for Mould Fabrication

2.6.3.1 Cast Resin Tooling

One of the most simple and inexpensive techniques of fabricating an injection moulding tool for thermoplastic parts is Cast Resin Tooling process. The basic process consists of mounting a pattern inside a mould frame, setting up a parting line, and then pouring resin over the pattern until there is enough material to form one half of the tool. After completion of the first half, the technique continues for the second half of the tool. There are numerous tooling resins available with different mechanical and thermal qualities with epoxy being one of the most popular materials. The resins are often filled with aluminium powder to enhance the thermal conductivity and compression strength of the tool and this also reduces the cost of the resin. Cast resin tools are typically used for up to 250 moulded parts, but in some cases it is possible to produce up to 1000 parts depending on the polymer material being moulded [27].

The main advantages of this technique are that it is fast, comparatively simple, and can be used to mould common thermoplastics such as polystyrene, polypropylene and ABS. Some disadvantages are the low mechanical strength of the moulds and low thermal conductivity which increases the moulding cycle time. Due to these reasons, this technique of rapid tooling is generally suitable for somewhat simple shapes [27].

2.6.4 Rapid Prototyping Technology for Injection Moulds

Manufacturing of injection moulds by conventional CNC machining or electric discharge machining techniques is very slow and costly. Expert tool makers are not easily available in the market. With the increase in product complexity and short product cycles, a large number of precision tools have to be made by a declining number of toolmakers [28].

Adapting a method which gives both time and labour savings and addresses these restrictions can be very beneficial. RP offers the prospects for improvement in mould development that can be achieved with subtractive technologies. RP technologies also have the ability to manufacture complex conformal cooling channels to offer better thermal performance and to use multiple materials to optimize moulds for performance and cost. This technology has given a strong and motivating force in the development of additive technologies for producing metal parts, as well as in material transfer processes that use RP patterns [28].

2.6.5 Limitations

The vision of RP technology is the direct manufacturing of injection moulds with the same level of accuracy and robustness as CNC methods. Even though great improvements have been made in that course, and time and labour savings are being realized by RP processes, the technology is still juvenile. The benefits realized are not widespread and must be tested for each case.

Rapid tooling techniques for injection mould fabrication should be considered for the following factors.

- When reduced time to market is required,
- For prototype and low volume production,
- Parts that may be difficult to manufacture due to their complex nature.

The general restrictions of RP techniques in comparison with CNC methods are:

- They produce less precise and less sturdy tools,
- They may have part size and geometry restrictions,
- Do not essentially make parts matching to machined tools
- Tools might not be easily modified using usual toolmaking techniques [28].

2.6.6 Selecting a Process

Selection of an RP process for a manufacturing application is an intricate issue. The factors to consider are

- The final application
- Production level
- Part dimension

- Precision
- Material requirements.

The knowledge of the existing RP technologies provided here gives a broad direction for selection and gives an opportunity to learn more about them. One important consideration is that at present, while direct RP tool making techniques might offer faster turn-around, one of the indirect techniques might offer lower expenses and higher precision. Another thing to consider is that sometimes it is suitable to manufacture one part of a tool with CNC technology and another part using RP processes. The most cost-effective and suitable method must be selected for each segment of a tool, and not necessarily for the tool as a whole [28].

Market acceptance for RP processes can be expected to increase, but is likely to remain thorough where the technology gives detailed benefits. However, the increased need for faster time to market, as well as more specific and shorter run products, means that while RP will not lead the field, it can achieve greater recognition as existing technical restrictions are overcome [28].

2.6.7 Direct Additive Fabrication of Injection Moulds

2.6.7.1 Stereolithography Based Tooling

Over the years much work has been done to directly fabricate injection moulds using stereolithography materials. One such process, Direct Accurate Clear Epoxy Solid (ACES), ACES Injection Moulding (AIM) developed by 3D Systems has gained much attention, but was not widely accepted because of its restrictions. The technique is useful to produce moulds for short run or prototype parts up to 50 of small and less complex thermoplastic parts. Sometimes, the moulds are reinforced with epoxy, depending on the part geometry. The moulds may need post processing to eliminate stair stepping and improve surface finish [29].

Parts produced with SLA moulds cannot match those made by high production metal moulds. Other problems are the cycle time which is comparatively long due to the lower thermal conductivity of the material, and the low pressures which must be used due to the reduced strength of SLA materials. To overcome the limitations of SLA tooling, newer materials are being introduced with higher strength and temperature resistance that can improve this method [29].

2.6.7.2 Metallic Soft Tooling

EOS or Electro Optical Systems based in Germany introduced a process called Direct Metal Laser Sintering (DMLS) which uses a bronze alloy which offered an improvement in soft tooling over SLA based moulds. DMLS uses materials that have more strength and increased thermal conductivity and produces moulds that are closer to conventionally fabricated metal moulds. The tooling fabricated with DMLS is porous, and needs infiltration with low melting point metal before use. DMLS moulds can produce several thousand parts but they still have limited life and generally cannot replicate fine details and must be finished before use. No secondary sintering and burnout cycles are required because the parts produced are already 95% dense. Another advantage of the DMLS process is higher detail resolution due to the use of thinner layers, enabled by a smaller powder particle size. This capability allows for more complex part shapes [29].

2.6.7.3 Metallic Hard Tooling

3D Systems developed the selective laser sintering (SLS) process for metallic tools and use a polymer based binder coated steel powders. After sintering, the binder is burned out leaving a green part that is porous. The green part is then infiltrated with bronze to get a fully dense mould with approximately 70% steel content. The SLS metal part production process has been significantly enhanced over the years to improve precision and resolution, and reduce stair-stepping [29].

These steel-based techniques offer the maximum benefit for small, complex geometry parts that would be hard to machine. Conformal cooling channels can be integrated into the moulds which can produce thousands of parts of almost any polymer material [29].

2.6.7.4 Selective Laser Melting (SLM)

MTT Technologies Group based in UK has developed the Selective Laser Melting (SLM) process known as the Realizer system. The technique is similar to SLS process; the difference is that the SLM machine fully melts metal or ceramic powders to produce fully dense parts. No post processing steps are required as compared to the porous parts produced by SLS. Any metal or ceramic powder can be used and a high finish is achievable. Several materials can be used in SLM system including tool steels, stainless steels, titanium and cobalt alloys [29].

2.6.7.5 Laminated Tooling

It is a substitute way to fabricating mould cavities directly on an RP machine. Using the same technique as the Laminated Object Manufacturing (LOM) process, sheet metal layers are cut to replicate slices from a CAD model. Laser or water jet cutting techniques can be used to produce the cross sections.

To fabricate a mould tool, the CAD model must first take the shape of the required cavity. By cutting all of the slices of the cavity in sheet metal, a stack of laminates is made to reproduce the original CAD model. Either clamping or bonding is implied; to make a solid mould cavity in hardened tool steel without requiring complex post process cutter path planning. The surface finish of the tools is generally poor due to the use of thick sheets, normally 1 mm. Therefore, some kind of finish machining is required [30].

Laminated tools have been used effectively for a variety of material processing methods like press tools, blow moulding and injection moulding. Tool life can be enhanced by hardening after cutting and lamination. However, part complexity is limited by layer thickness.

One major benefit of laminated tooling is the capability to change the design of parts quickly by replacing laminates if un-bonded. Conformal cooling channels also are easily integrated within the tool design and laminated tooling can be used for large tools. The need for finish machining to remove the stair steps is the main drawback of this process [30].

Cheah et al. [31] did an experimental study on the fabrication of injection mould with aluminium-filled epoxy. In their research, an epoxy resin mould was tested and characteristics of the end product were presented. Mould fabrication is carried out using an indirect rapid soft tooling approach. In the indirect soft tooling method, RP technology is employed to make the master pattern of the required final product before the mould halves are cast from tooling materials. The tooling material used for the study was MCP EP-250 aluminium filled epoxy resin. The core and cavity fabricated in the research is shown in Figure 2.7.

Figure 2.7 Injection Moulding core and cavity produced with RT [31]

Another research and development study of rapid soft tooling technology for plastic injection moulding was done by Ferreira and Mateus [32]. The main objective of their work was to suggest some original ideas to integrate rapid prototyping and rapid tooling to manufacture plastic injection moulds with composite materials like aluminium filled epoxy and cooled by conformal cooling channels. The objective was to improve an algorithm for decision to assist the technology and materials selection.

The different devices and types in soft tooling were verified with some case studies applying RT technology to fabricate injection moulds for polymers.

Rapid tooling technology is basically a process that adopts RP methods and applies them to tool and die fabrication. A comparative study on various RT techniques was done by Chua et al. [33]. In their study, several established RT methods are discussed and classified. An evaluation was also made on these methods based on tool life, tool manufacturing time and cost of tool development. The importance and benefits of rapid tooling were also discussed in the study. They also described that RT is most appropriate for pre-series production. This involves fabrication of the product in its final material and by the proposed manufacturing process, but in small numbers. Pre-series production is typically to check production equipment and tools and to analyze the market introduction of a product.

Some researchers used moulds in injection moulds fabricated with SLA process. SLA and aluminium moulds were compared in a study by Hopkinson and Dickens [34]. Comparisons were made with regard to the ejection forces needed to push parts from the moulds, heat transfer within the tools and the surface roughness of the tools. Their results show that ejection forces for both types of tools increase when a longer cooling time proceeding to ejection is used. The ejection forces needed from a rough aluminium mould were greater than those from a smooth aluminium tool. Potential advantages of the low thermal properties of the tool were also discussed.

Another research by Ribeiro et al. [35] was on the thermal effects of SLA tools. In their work, the changes in SLA resin mechanical properties through the injection moulding were evaluated. A SLA mould was fabricated and utilized to inject small flat parts. Tensile test parts made from SL resin were positioned in the recesses within the tool and plastic parts were injected. After injecting a fixed number of mouldings, tensile tests were done using the tensile test parts. Tensile tests results showed that the thermal cycling encountered during the injection moulding process did not considerably influence the mechanical properties of the resin. Observations showed that decrease in the temperatures encountered in the tool may lead to longer tool life.

A study by Rahmati and Dickens [36] was on the evaluation of rapid injection mould tools fabricated directly by SLA process. SLA epoxy tools were able to tolerate the injection pressure and temperature and 500 injections were attained. The tool failure mechanisms during injection were investigated and it was found that tool failure either occurs due to higher flexural stresses, or because of higher shear stresses.

Due to the use of metallic materials, research has been done in using SLS for IM tooling. One such study by Barlow et al. [37] presented the mechanical characteristics of a new mould making material, planned for fabricating injection mould inserts for polymers by SLS process. Although the strength of this material is considerably lower than that of the tool steel usually used to manufacture moulds, design calculations indicate that it can still be used for mould insert production. It was also pointed out that this material has a lower thermal conductivity value as compared to steel but it is higher compared to that for plastic melts. From calculations, it was showed that appropriate choices of conduction length and cycle time can decrease differences, related to steel moulds, in the operational behaviour of moulds made of the new material. The durability of example moulds was also discussed.

An experimental study on hybrid moulds was done by Godec et al. [38]. Their research highlighted comparative experimental analysis for hybrid and standard moulds on the properties of moulded parts and the processing parameters. They described hybrid moulds as the moulds fabricated with SFF technologies, differently from conventional moulds. Materials for hybrid moulds can be

- Epoxy
- Steel Powder

The material used in the study was a steel powder used in the process was called indirect metal laser sintering (IMLS). In the case of hybrid moulds this analysis enables the optimization of processing parameters. It was established that hybrid moulds can be effectively applied for producing thin-wall parts with a few restrictions. The differences in thermal properties of mould materials resulted in diverse part properties and mould cavity wall temperature fields. These differences can be minimized by optimizing the processing parameters. They also inferred that

RT technologies can be usefully applicable for rapid fabrication of injection moulds. The experimental mould inserts used in the research are shown in Figure 2.8.

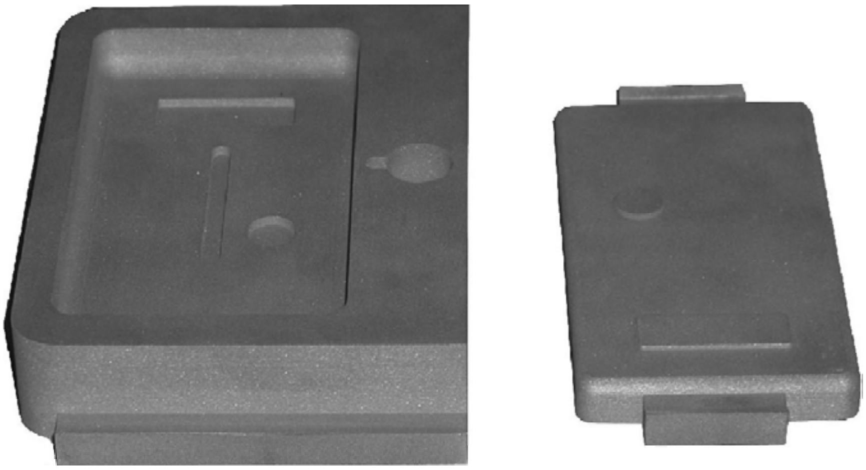


Figure 2.8 Experimental rapid tool mould inserts [38]

2.7 Injection Mould Cooling

Injection moulding is a common plastic processing method and is a vast business in the worldwide plastics industry [39]. In the injection moulding process, the melted polymer is injected inside the mould cavity to take the shape of the cavity and become an injection moulded part. The part needs to be cooled before it can be ejected from the mould to avoid shrinkage and part warpage. Mould cooling, sometimes referred as mould thermal management, is a vital issue in plastic injection moulding process and has major effects on production cycle times that is directly related with cost and also has effects on part quality. Cooling system design has great implication for plastic products made by injection moulding. It is vital not only to reduce moulding cycle time but also it considerably affects the productivity and quality of the product. Conventionally, injection moulding is cooled with the flow of a cooling medium, usually water, which is provided by straight drilled cooling channels in the injection mould [39].

2.8 Conformal Cooling Channels in Injection Moulds

Conventional cooling channels are usually fabricated with straight drilled holes in the mould, which have geometric and cooling fluid mobility limitations (Figure 2.9). The technique of conformal cooling has been introduced as an effective alternative to conventional cooling [2]. Thermal management of injection moulds is very much enhanced with the application of conformal cooling channels as compared with conventional method of cooling with straight drilled holes.

The cross section of conventional cooling channels is circular due to the manufacturing process of drilling. Rapid Tooling (RT) technologies have the capability of fabricating conformal channels which can have circular or non-circular geometries.

The concept of conformal cooling in injection moulds has been experimented and published by various researchers [5, 40, 41, 42, 43, 44, 45, 46].

One of the benchmark studies on the technique of conformal cooling was done by Sachs et al. [5]. The experimental study was on the fabrication of injection mould with conformal cooling channels (CCC) using the 3DP technique. Conformal channels were incorporated both in the core and cavity of the mould. Comparison was done for conformal channel mould with a mould having straight channels. Thermocouples were embedded in the core and cavity which indicated that the conformal tool had no transient behaviour at the beginning of moulding process, while the mould with straight channels took more than 10 cycles to come to a steady state temperature condition. The conformal tool also maintained a more consistent temperature within the tool during a separate moulding cycle. The injection moulding core and cavity fabricated with 3DP process is shown in Figure 2.9. Figure 2.10 indicates the temperature versus time graph for straight and conformal cooling channels.

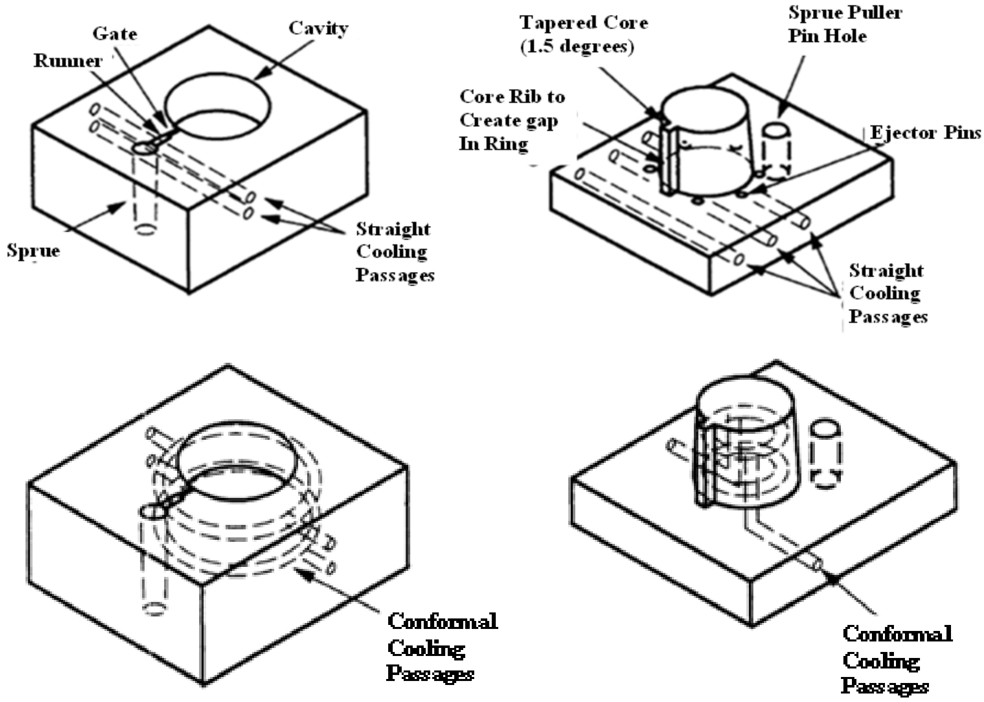


Figure 2.9 Straight and Conformal Cooling Channels [5]

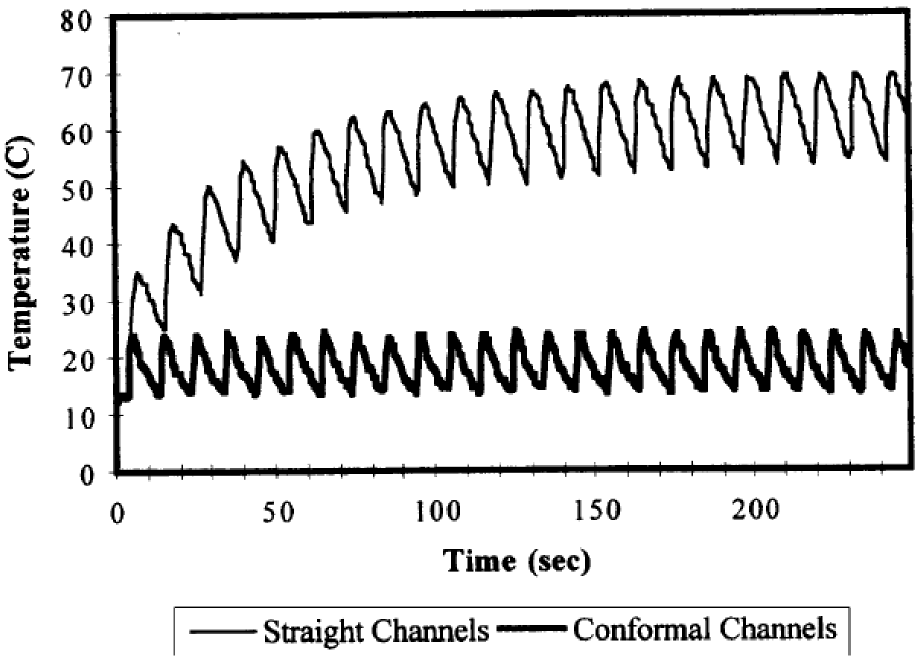


Figure 2.10 Mould Surface Temperatures [5]

Another research by Rannar et al. [40] was on the fabrication of conformal cooling channels within moulds fabricated by Electron Beam Melting (EBM) process. Their main study was on the comparison of cooling times and dimensional precision of conventional injection mould cooling channel using straight holes and RP fabricated layout, manufactured by electron beam melting (EBM) technique. A test part was designed in order to reproduce the vital problem of insufficient cooling in cores. The part and cooling layouts were analysed by simulation software and the results were compared with experimental results. The analyses indicated an enhancement in cooling time as well as in dimensional accuracy in favour of conformal channels manufactured by EBM, and they were obtained using a particular part. The insert produced with EBM technology is shown in Figure 2.11.

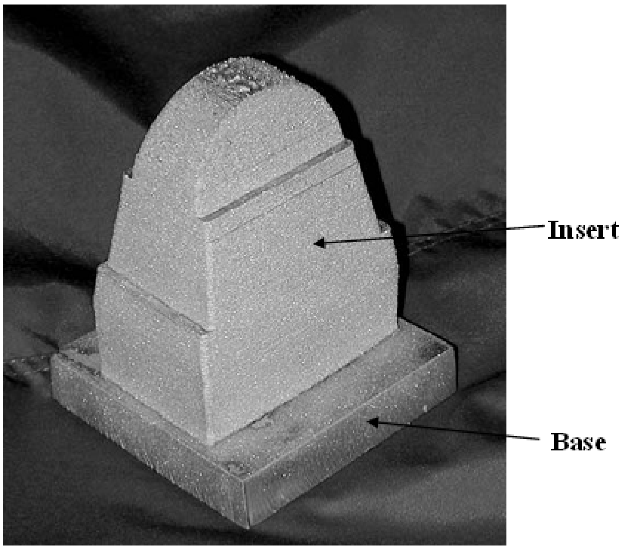


Figure 2.11 Insert fabricated by EBM [40]

Another research conducted by Villalon [41] was on the fabrication of injection mould with conformal cooling channels with EBM process. In this work, a new process for manufacturing rapid tools was proposed. It was found that using the EBM process, certain features in the mould can be optimized such as the cooling system that is of critical importance in the part cycle time of a tool. A heat transfer simulation study was carried out to find the effect of conformal channels in the heat dissipation within a mould. Extensive experimentation was performed to obtain valuable guidelines for the design of conformal channels in injection moulds manufactured via EBM technology. The author also pointed out that, when the moulded part has curvature, spots closer to the cooling channels can give rise to differential cooling and consequent warping.

Xu et al. [42] did their study on the design of conformal cooling channels in injection moulds with SFF methods which have the capability to fabricate moulds with conformal channels. They observed that tools with conformal channels have established enhanced production rate and part quality as compared with conventional mould. They presented their work on a modular approach to the design of conformal channels. Their methodology was verified through application to an intricate core and cavity for injection moulding process.

A study by Yoo [43] was on Profiled Edge Laminae (PEL) method, which is a thick-layer laminated RT technique. The advantage of RT techniques is agility in building conformal cooling or heating channels within a mould for improved thermal control, but mould tool sizes are restricted. He described that the ability to integrate conformal channels of any shape and routing into tools made by RT techniques will give tool designers a unique flexibility with temperature control of moulds. The main emphasis of his study was on the heat transfer performance of conformal channels for rapidly fabricated tools used in manufacturing with moderate temperature and pressure conditions.

Au and Yu [44] presented a design study of variable radius conformal cooling channel (VRCCC) to achieve more uniform cooling performance. Thermal-FEA and melt flow analysis were used to validate the method. VRCCC is the cooling layout that conforms to the contours of moulding part geometry with various diameters along the coolant flow. It takes advantage of the Solid Free Form (SFF) technologies to produce a curvilinear geometry of conformal cooling channel (CCC) and integrate with changing diameters along the axis of cooling layout for the rapid tool. They proposed and verified the VRCCC design and fabrication based on contemporary SFF technologies with thermal FEA and melt flow analysis. Their analysis work indicated that heat transfer from the mould cavity surface to the cool medium circulation via VRCCC has better cooling performance and higher part quality. The VRCCC described in the study is shown in Figure 2.12.

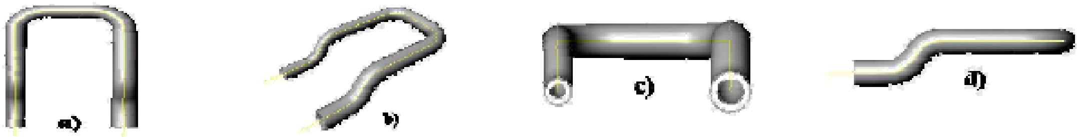


Figure 2.12 Various VRCCC designs [44]

Another study done by Park and Pham [45] was on the designing of a conformal cooling system that gives uniform cooling over the whole mould surface with least cycle time. Their main objective was to minimize the cooling time with a realistic design that will improve the cooling system design in terms of cooling channel size and position. Their work presented a technique for the design of conformal channels which leads to a more effective control of the mould temperature through conformal cooling. They concluded that SFF techniques can build injection moulding tools with complex cooling channels which can have considerable enhancement in production rate and quality of parts.

An experimental study by Saifullah et al. [46] was on a square sectioned conformal channel system for injection moulds. Simulation and experimental confirmation were conducted with these new cooling channels systems. Experimental verification was done for a test part with a portable injection moulding machine. Their paper described new comparative results based on temperature division on mould surface, cooling time and hardness of the part. Their results provide a consistent distribution of temperature and hardness with reduced cooling time of the part. Figure 2.13 shows the comparative temperature plot of square section channels with circular channels.

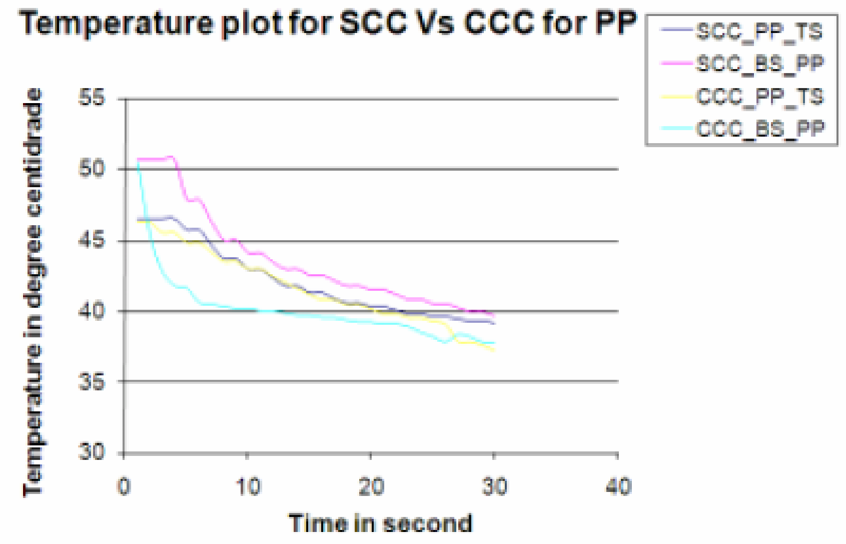


Figure 2.13 Comparative Temperature Plot [46]

2.9 Thermal Analysis

The thermal analysis in engineering applications calculates the temperature distributions and other thermal attributes in a part or system. Generally, these thermal quantities are:

- Temperature distributions
- Amount of heat gained or lost
- Thermal gradients
- Thermal fluxes

2.9.1 Types of Thermal Analysis

2.9.1.1 Steady-state Thermal Analysis

A steady state thermal analysis decides temperature distributions and other thermal properties under steady state conditions. A steady state condition is one where heat storage effects can be neglected with a change in period of time.

The application of steady state thermal analysis is to determine temperatures, thermal gradients, heat flow rates, and heat fluxes in an article that are induced by thermal loads that do not change with time. A steady-state thermal analysis calculates the effects of steady thermal loads on a system or part. In engineering applications, a steady state thermal analysis is often carried out before doing a transient thermal analysis, to establish base conditions. A steady state analysis could also be the last step of a transient thermal analysis, executed after all transient effects have faded out. A steady state thermal analysis could be linear, with constant material properties, or nonlinear, with temperature dependent material properties. The thermal properties of many materials do change with temperature, so the thermal analysis typically is nonlinear [47].

2.9.1.2 Transient Thermal Analysis

In transient thermal analysis, determination of the temperature distributions and other thermal properties is done under conditions that change over a phase of time. The change in the temperature distributions over time is of significance in many engineering applications. Many heat transfer applications such as electronic packaging design, heat treatment problems, engine blocks and pressure vessels involve transient thermal analysis [47].

A transient thermal analysis could also be linear or nonlinear. The thermal properties of many materials do change with temperature, so the analysis is typically nonlinear. Basically, a transient thermal analysis adopts the same technique as a steady state thermal analysis. The primary difference is that applied loads in a transient thermal analysis are functions of time [47].

Dimla et al. [4] presented work on the design and optimization of conformal cooling channels in injection mould tools. The emphasis of this study was to verify a design for conformal channels in an injection mould using thermal analysis. 3D CAD model of a component appropriate for injection moulding was designed and the core and cavity required to mould the part were produced. Thermal analyses were used to determine the best position for the gate and cooling channels. These two factors give the most benefit in the cycle time. Analysis of CAD models indicated that tools with conformal channels had a considerably reduced cooling time and enhancement in surface finish when comparing with a conventionally cooled mould.

A study by Saifullah and Masood [2] was on the finite element thermal analysis of conformal cooling channels in injection moulding. They found out that effective cooling channel design in the mould is important because it not only affects cycle time but also the part quality. Conventional cooling channels are made of straight drilled holes in the mould, which have limitations in geometric complexity as well as cooling fluid mobility within the injection mould. The main objective of their study is to determine an optimum design for conformal cooling channel of an injection moulded plastic part using finite element analysis and thermal heat transfer analysis. Their work on thermal analysis predicted that mould with conformal cooling channels indicated a considerable reduction of cooling time and improved part quality. The ANSYS temperature contour plot is shown in Figure 2.14.

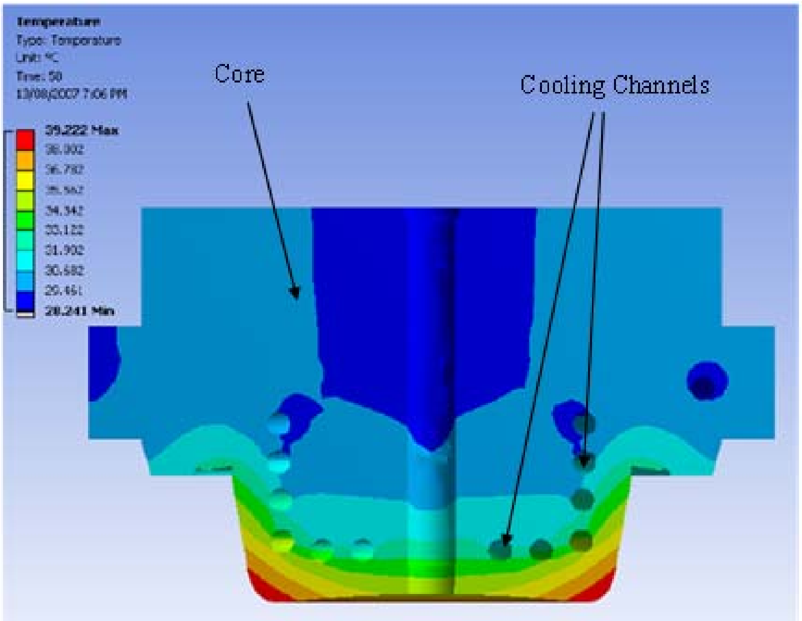


Figure 2.14 Temperature distribution of Conformal cooling channel mould [2]

Another study by Saifullah and Masood [48] was on optimized mould design of conformal cooling channel for a plastic part. Core and cavities were designed and circular configurations of conformal cooling channels were developed. The part cooling time has been optimized by using these conformal cooling channels and compared with straight channels in the mould using thermal simulation software. They presented the results based on temperature distribution and cooling time using transient thermal analysis conditions. Their findings provided a reduction in cooling time for the plastic part, which could lead to increase of production volume. An advanced technique of cooling system that surrounds or conforms to the shape of the part in the core and cavity can be manufactured by rapid prototyping and rapid tooling techniques. The temperature distribution contour plot for conformal cooling channel mould can be seen in Figure 2.15.

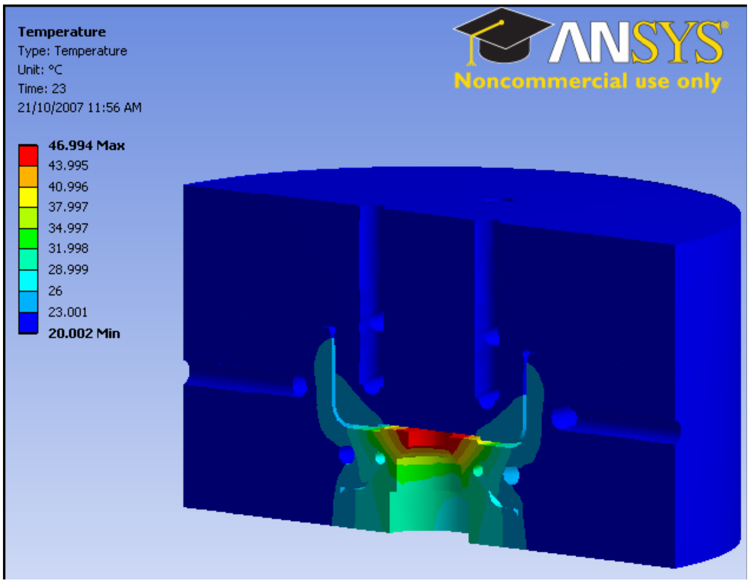


Figure 2.15 Temperature distribution in the conformal cooling channel mould [48]

A procedure presented by Bart and Hanjalic [49] is for getting a shape factor for transient heat conduction in random items for which no analytical solution exists. Such a shape factor is the primary parameter in the calculation of the heat transfer procedures. The technique has been applied and equates favourably with other existing methods. Some data is given for transformation between the different parameters that are in use to explain shape or geometry, including those for an equivalent one-dimensional object.

Another study done by Nickolay et al. [50] was on the application of Finite Elements and the Method of Finite Differences for the calculation of shape factors for cross-sections surrounded by concentric circles and squares. It was pointed out in the study that for some basic and well defined geometries, it is possible to calculate the shape factor by the technique of conformal mapping. They described that two-dimensional steady heat flow in bodies with different cross-sections and isothermal boundaries is a problem that has been investigated thoroughly in the literature. By formulating the shape factor for the investigated cross-sections, analytical approximations for the shape factor were found. The approximations accomplish limiting cases and are close to the accurate solutions when fitted to the numerical values.

2.10 Summary

A comprehensive literature review has been done to determine the current status of research in the area of thermal performance of injection moulds using various RP and RT technologies. From the literature review the argument has been built towards the research objective of comparative evaluation of moulds fabricated with aluminium filled epoxy. Also the unresolved problem of enhancement of mould cooling has been identified as a potential research area. This objective is accompanied by the associated requirements of design and fabrication of injection moulds of different configurations. It is concluded that valid approaches to mould cooling enhancement lie in geometric modifications to the cooling channel and to the mould.

The various RP and RT technologies are being studied these days by many researchers. These studies are proving the importance of RP and RT technologies in the manufacturing market. From this review, several opportunities for research have been identified. Due to the primary influence of thermal performance in the injection mould, the effects of profiled channels and the influence of conducting thermal inserts embedded inside the epoxy moulds will be investigated in this work.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The methodology adopted for the research includes thermal analysis of encompassing the use of conduction shape factors and transient thermal analysis for the moulds. The design of cooling channels plays a very important role in the injection mould tool. The first phase of methodology includes steady state and transient thermal analysis. Thermal analysis was conducted on different cooling channel geometries to find the optimum geometry for the injection mould. The conduction shape factor is a technique that can be used for evaluating different channel shapes for arriving at the best cooling channel geometry among given choices.

The reason for analysis and simulation in engineering research is to avoid the cost of re-engineering. The research process can be simulated before the actual experiment. This is also true for injection moulding experiments. It would be advantageous to use numerical simulation tools to study the heat transfer behaviour of the melted polymer through the mould cavities.

For the second phase of methodology, the design and development of the mould having circular conformal cooling channels (CCCC) and profiled conformal cooling channels (PCCC) and the concept behind the design are discussed. The specification of the mould design was based on the Vertical Injection Moulding (VIM) machine which was used for the experiments. Epoxy moulds were cast and used with an aluminium frame that could withstand the clamping forces of the VIM machine. Another idea for further enhancing the heat dissipation rate of epoxy moulds is also presented. The basic concept behind the approach was to embed thermally conducting inserts within the mould between the cavity and the cooling channel. This technique is envisaged to increase the effective thermal conductivity of the epoxy mould, leading to further reduction in cooling time for the part.

3.2 Conduction Shape Factor

Conduction Shape Factor is a technique with analytical solutions in Heat Transfer where two dimensional heat conduction problems are reduced to an equivalent one dimensional problem. It is an important class of heat transfer problems for which simple solutions are obtained for a geometry that consists of two surfaces maintained at constant temperatures T_1 and T_2. The shape factor method permits a rapid and easy solution of multi-dimensional heat transfer problems where it is applicable. The conduction shape factor S is defined by the relation:

$$q = Sk(T_1 - T_2) \tag{3.1}$$

where,

'q' is heat flow,
(T_1-T_2) is a specified temperature difference,

'*k*' is the thermal conductivity of the medium between the surfaces, and

'S' is the Conduction Shape Factor.

The conduction shape factor depends on the geometry of the system. In equation 3.1, 'S' is determined with the dimensions of length (m, mm etc.). Once the value of the shape factor is determined for a specific geometry, the steady heat transfer rate can be calculated from the equation above using the specified constant temperatures of the two surfaces and the thermal conductivity of the medium between them. Conduction shape factors are only applicable when the mechanism of heat transfer between the two surfaces is limited to conduction heat transfer and governed by the Fourier law of conduction.

$$q = kA\frac{(T_1 - T_2)}{L} = Sk\,(T_1 - T_2) \tag{3.2}$$

$$S = \frac{A}{L} \tag{3.3}$$

q = heat flow (watts)

k = thermal conductivity (W/mK)

A = area (m^2)

(T_1-T_2) = temperature difference (^oC)

L = path length

S = area / path Length

3.2.1 Calculation of Shape Factor

The finite element technique, as used by Nickolay et al. [50], is adopted here. Modelling a thin slice of the mould cavity and cooling channel shape was done using CAD solid modelling software. A typical CAD model is shown in Figure 3.1.

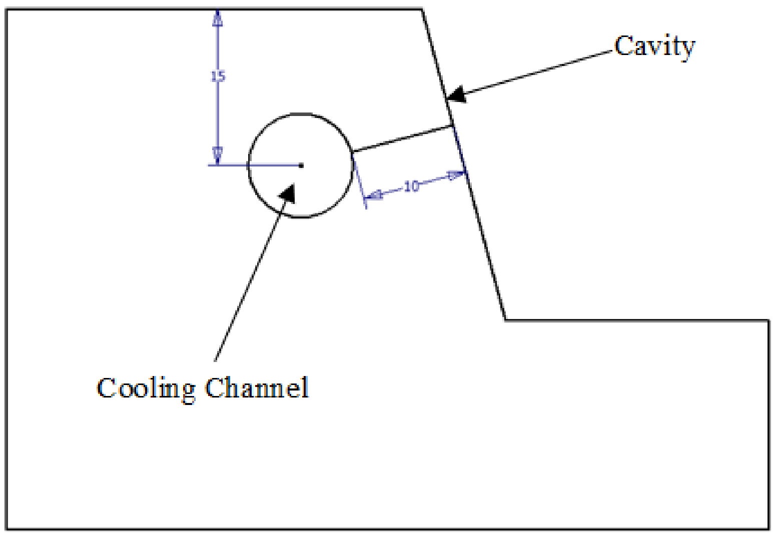


Figure 3.1 CAD model for Cavity and Channel

The CAD model is transferred into ANSYS software for thermal simulation. Initial and boundary conditions and thermal loads are applied to the model. Steady state thermal analysis is performed on the mould cavity slice. A steady-state thermal analysis calculates steady thermal loads on a system or element. Engineers/analysts perform a steady-state analysis prior to doing a transient thermal analysis, to assist in establishing initial conditions [47].

The channel shape which has a high value of shape factor is a better choice for cooling channel geometry. Different channel geometries were modelled and thermal simulations were carried out to determine the different parameters for the calculation of shape factors. All channel shapes have the same cross sectional area of 78.5 mm^2 and are compared to a circular shape of diameter 10 mm, with the same cross sectional area for flow of 78.5 mm^2.

3.2.2 Modelling for other Channel Geometries

Other channel geometries were modelled with the same cross-sectional area and same distance from the cavity plane as shown. The models for channel geometries are shown in Figures 3.2 to 3.5.

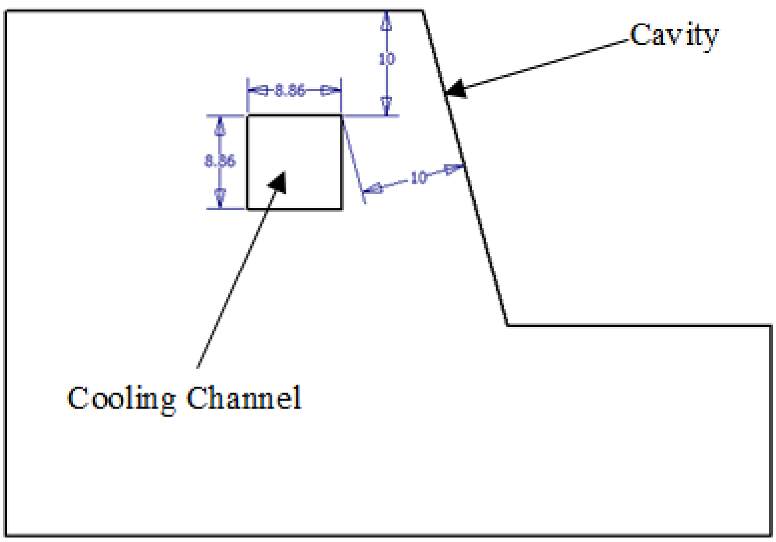


Figure 3.2 Square Channel Geometry model

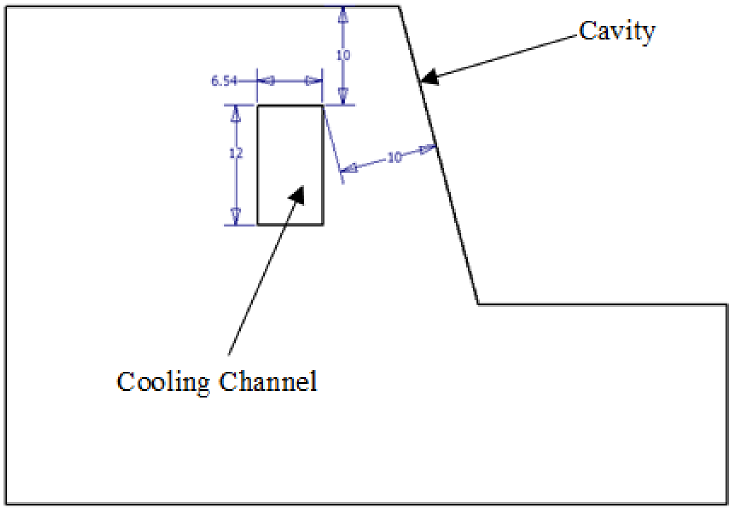


Figure 3.3 Rectangular Channel 1, Geometry model

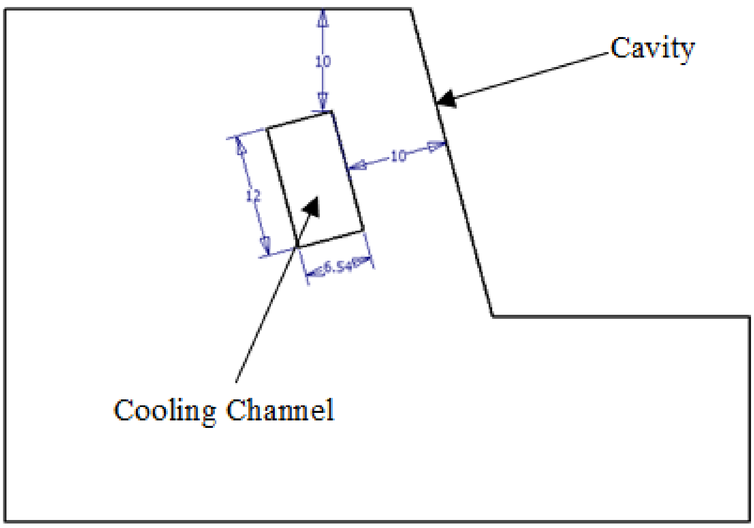


Figure 3.4 Rectangular Channel 2, Geometry model

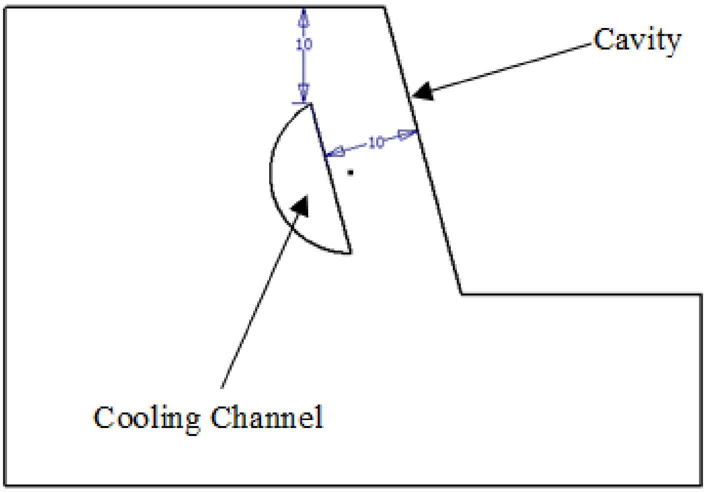


Figure 3.5 Profiled Channel Geometry model

3.3 Injection Moulded Part Design

The part to be moulded was designed like a cup structure with a wall and base thickness of 5 mm. This design for the injection moulded part would help in avoiding sinks and voids which occur in parts which have thicker sections. The moulded part design is shown in Figure 3.6 and part drawing is given in Appendix A.

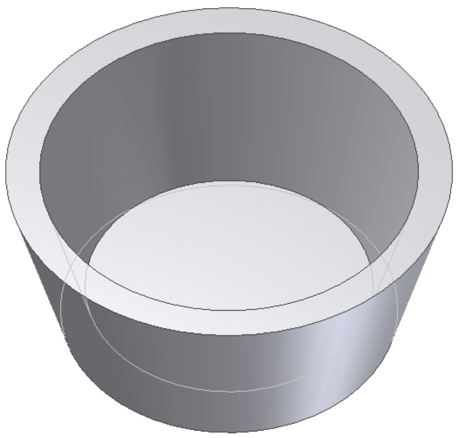


Figure 3.6 Injection Moulded Part

The basic idea for the geometry of the injection moulded part for the current research was taken from the work done by Sachs et al. [5] as shown in Figure 3.7. The part design was changed by increasing the outer wall angle for the part and adding a base to it. The wall taper angel was increased for the ease of ejection of the injection moulding part form the mould.

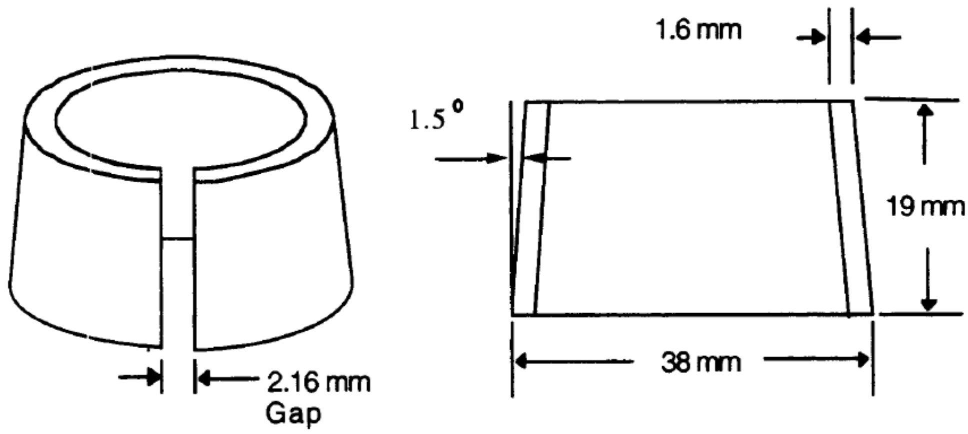


Figure 3.7 Part used in the research by Sachs et al. [5]

3.4 Design/Dimensions for Circular Channel

While designing the circular channel, the following factors were considered. If the channel diameter is too small it (i) could choke the coolant flow (ii) the small diameter channel has a larger velocity of coolant for a given flow rate which could erode the channel faster on the inside. At the same time a larger diameter channel could affect the structural integrity and strength of the mould. Hence after several design iterations, a channel diameter of 10 mm was seen to be appropriate and therefore selected for the design and fabrication of the circular cooling channel in the epoxy moulds. Also the solid modelling design indicated that for the given dimensions of the moulds, the 10 mm diameter channel was suitably appropriate for the mould in terms of geometric comparison.

3.5 Design of the Profiled Channel

The sketch for the profiled channel is given in Figure 3.8.

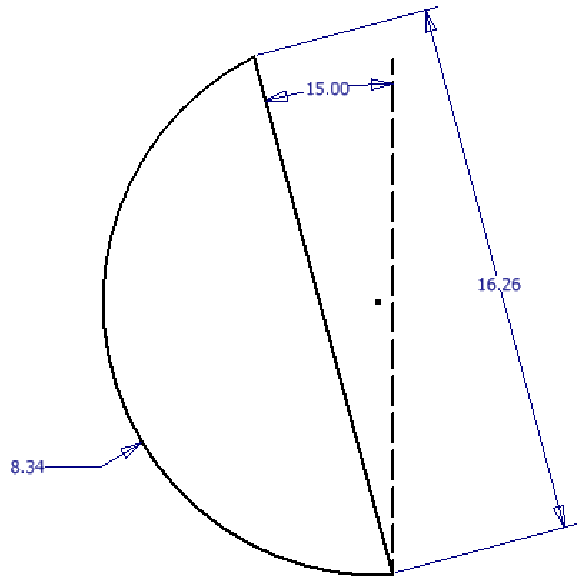


Figure 3.8 Profiled Channel

The profiled channel is designed so that its cross sectional area is the same as for the circular channel (78.5 mm^2). The profiled channel is tilted at an angle of 15^o so that the surface of the channel facing the mould cavity is parallel to the cavity wall.

3.6 Trial Experiment for the Determination of Simulation Parameters

Obtaining simulation parameters, like the initial and final temperature of the mould for the simulation were found to be impossible by literature study or through trial simulations. To overcome this problem, it was decided to perform a trial experiment with the base case, which is mould with circular conformal cooling channel (CCCC). The mould was fabricated with epoxy having CCCC and embedded thermocouples. The mould was placed in the vertical injection moulding machine and trial injection moulding runs were done. The measured temperature of the water flow through the CCCC was found to be in the range 29-30^{o}C. After a few trial runs, it was seen that the appropriate temperature of ejection of the part, as measured by part thermocouples, was 35^{o}C, at which the part had attained enough solidity to be ejected without distortion. Thus the simulation end temperature was determined as 35^{o}C. The temperature for reaching 35^{o}C was achieved at about 1000 seconds during the trial experiment. So the simulation end time was decided as 1200 seconds. As the cooling water continued to flow through the mould during the subsequent operations after ejection and the cooling water temperature was observed as about 30^{o}C, the initial mould temperature was decided as 31^{o}C.

As the injection moulding machine is manual and after every moulding run, the machine is stopped and the part is taken out from the mould manually. When the part temperature reaches 35^{o}C it is taken out from the mould. Also at this temperature, it gives enough time for the mould to be assembled back for the next moulding run. The time between the moulding cycles is such that the mould temperature does not fall below 31^{o}C and the next moulding run can be started at 31^{o}C. Then when the temperature reads 31^{o}C again, the next moulding run can be started.

The peek temperature for the basic case of mould with CCCC measured at the mould cavity walls with the embedded thermocouples was 77^{o}C. Mould was initially at 31^{o}C and with melted polymer injection the temperature gradually increases and peeks at 77^{o}C in 30 seconds. From this initial experiment, the input data was obtained which will be used as initial condition to get the cooling time. This input data will be used for all mould configurations. The purpose of the present simulations is to predict the cooling time for all mould configurations.

3.7 Design of Mould Cavities for Simulation

The numerical model of mould cavities to be used for the thermal simulation was identical to the one used for the manufacturing purpose. The model was developed in such a way as to make the application of boundary conditions convenient. The models for the cavities are shown in Figures 3.9 and 3.10.

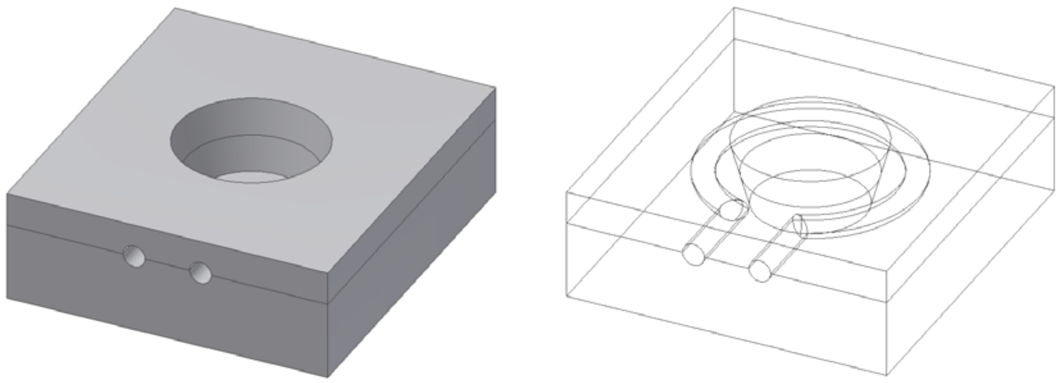


Figure 3.9 CAD and Wire-frame Models for Circular Conformal Cooling Channel Mould Cavity

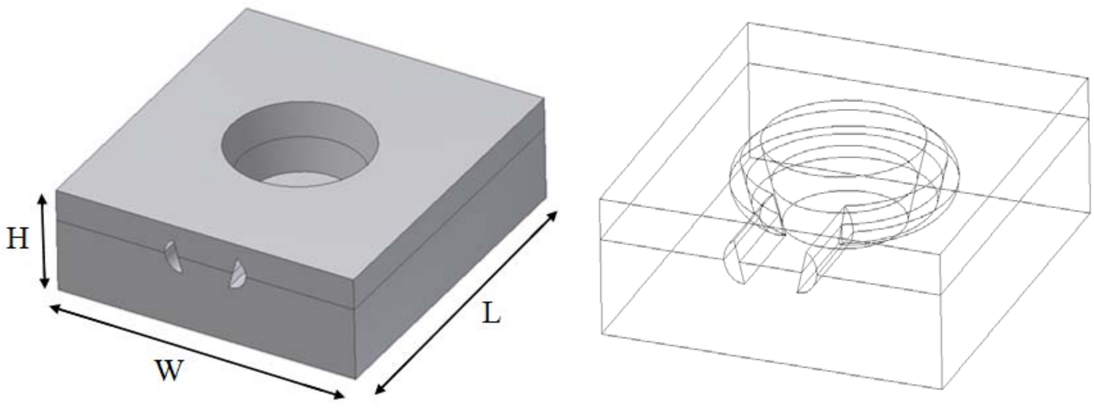


Figure 3.10 CAD and Wire-frame Models for Profiled Conformal Cooling Channel Mould Cavity

3.7.1 Mathematical Model for Simulation

This is a standard heat transfer model which is used to solve the current problem. The vectorial form of the general heat conduction equation is given by

$$\frac{\partial}{\partial t}(\rho C_p \mathrm{T}) = \nabla \cdot (\mathrm{k}\nabla T) + \dot{q} \tag{3.4}$$

where

ρ = Density (kg/m^3)

C_p = Specific Heat (J/kg^{o}C)

T = Temperature (^{o}C)

k = Thermal conductivity (W/mK)

$\dot{q}$ = External Heat source (watt)

t = Time (seconds)

Assuming $\dot{q}$ =0 in equation 3.4, and all properties are temperature independent

$$\rho C_p \frac{\partial T}{\partial t} = k \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right]$$

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_p} \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right]$$

$$\frac{\partial T}{\partial t} = \propto \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right]$$

where $\frac{k}{\rho C_p} = \propto$ which is the thermal diffusivity.

3.7.2 FEA Model for Simulations

The CAD solid model data is imported into ANSYS environment via the design modeller module. The CAD model was imported into the design modeller module which can import most of the popular CAD software's models. From the design modeller, the FEA model is taken into the Ansys environment for thermal analysis.

After importing the model into ANSYS, the next step is the mesh generation for the model. The technique adopted for this was mechanical mesh with automatic patch conforming/sweeping mesh option shown in Figure 3.11.

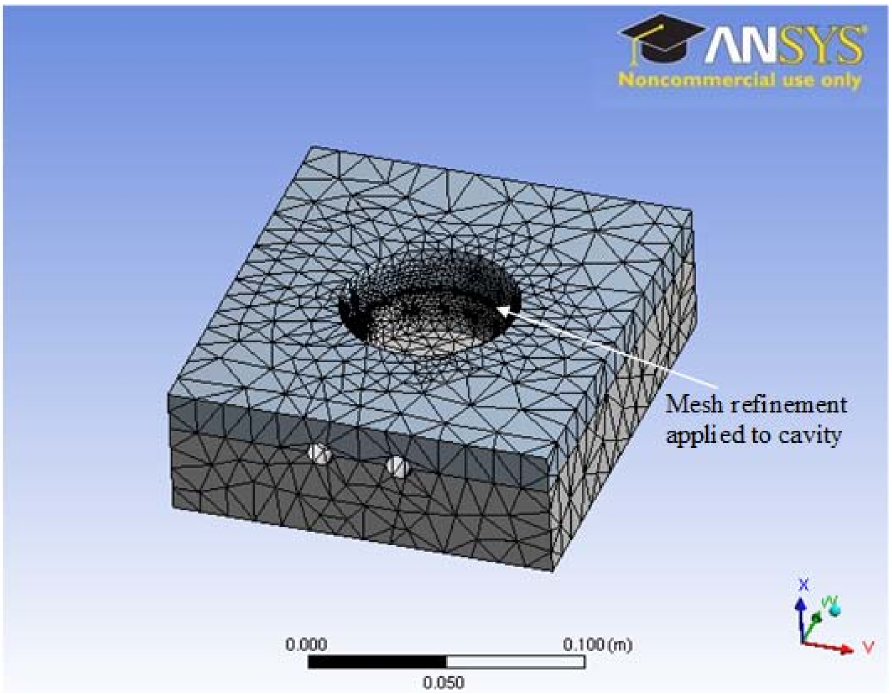


Figure 3.11 Mesh for FEA model

The statistics for the mesh are

Number of elements 25812

Number of nodes 39904

Mesh refinement was applied to the cavity surface to further refine the mesh.

Analysis type selected was Transient Thermal from the new analysis menu. Initial condition was selected as 31°C.

Analysis Settings (CCCC Mould Cavity)

No of Steps	2
Duration of time Step 1	30 seconds
Duration of time Step 2	1200 seconds

3.7.3 Initial and Boundary conditions

The simulation has been divided into 2 steps that is heating and cooling phases.

Step 1 Heating Phase

This is to provide the required initial condition for cooling phase.

Initial condition for step 1

T (x, y, z, 0) = 31^{o}C

Boundary condition for step 1

Adiabatic condition is assumed for all exterior surfaces other than the cavity surface by applying; q = 0 (adiabatic condition).

The heating phase is modelled by allowing the cavity surface to reach 77^{o}C in 30 seconds time interval obtained from the trial experiment.

Boundary condition applied to cavity = 77^{o}C

Convection condition was applied to the cooling channel surface with following parameters shown in Figure 3.12.

Convection coefficient	4799 W/m^{2o}C (calculated in 3.7.4.1)
Temperature	30^{o}C (From initial experiment)

Step 2 Cooling Phase

Initial condition for step 2

Initial condition for the cavity surface T (at t=0) = 77^{o}C

Boundary condition for step 2

Adiabatic condition is assumed for all exterior surfaces other than the cavity surface by applying; q = 0 (adiabatic condition).

Convection condition was applied to the cooling channel surface.

Convection coefficient	4799 W/m^{2o}C (calculated in 3.7.4.1)
Temperature	30^{o}C (From initial experiment)

Assumptions

Material properties are temperature independent

Coefficient of convection is constant

External surfaces are assumed to be adiabatic.

Constant temperature applied to cavity.

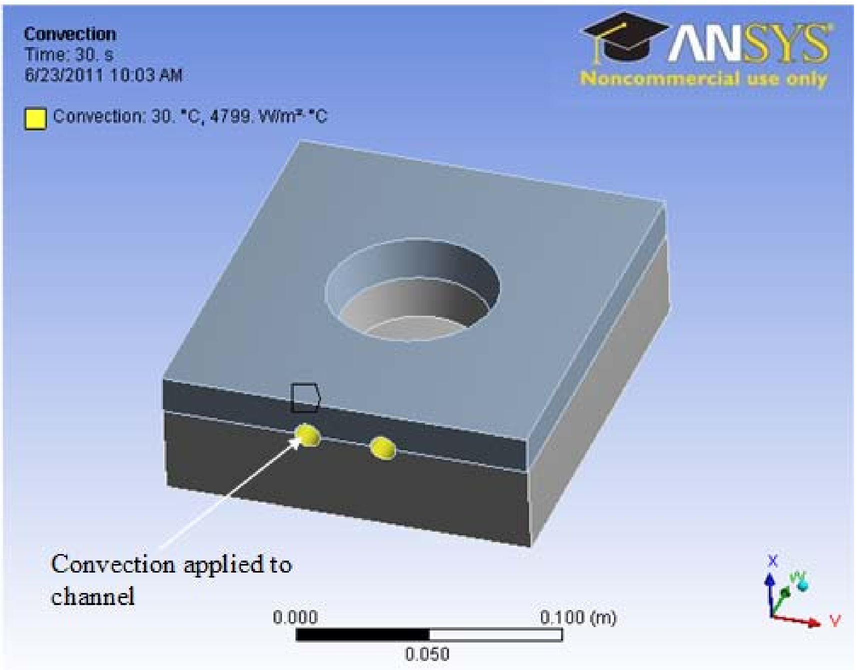


Figure 3.12 Convection applied to the cooling channel

From the data analysis of the initial experiment, it was observed that the temperature of the cavity was increased to 77^oC in 30 seconds before the temperature starts to drop. This temperature condition was applied in the simulation. The temperature of the cavity was allowed to increase to 77^oC in 30 seconds to simulate mould fill which was obtained from initial experiment and then the temperature was deactivated in the second time step. For the measurement of cavity temperature during the simulation, temperature probe was applied to the cavity surface. External surfaces of the mould are assumed to be adiabatic.

3.7.4 Inputs for the Simulation

The inputs for the computation are listed in this section.

Flow rate of water = Q = 4 litres/minute = 0.000066 m^3/second

Diameter of channel = 10 mm = 0.01 m

Area of channel = 0.0000785 m^2

Converting flow rate into velocity,

$$V = \frac{Q}{A}$$

Velocity = 0.85 m/s

Density of water, (ρ) at 30^{o}C = 995.6 kg/m^3

Dynamic Viscosity of water, (μ) at 30^{o}C = 0.798 mPa.s = 0.798 x 10^{-3} kg/m.s

For CCC, diameter = 10 mm = 0.01 m

Area of flow cross-section = $\pi D^2/4$ = 78.5 mm^2

The convective heat transfer coefficient values for circular cross-sectional channels and profiled cross-sectional are expected to be different due to the shape of the channels and therefore the different hydraulic diameters. This coefficient can be found by calculating Reynolds number and then calculating the value for "h" for both types of channel from heat transfer correlations.

3.7.4.1 Calculation of Convective Heat Transfer Coefficient "h"

The heat given up by the mould is ultimately removed by cooling water flowing in the cooling channels. The values of convective heat transfer coefficient for water for the channels of circular cross-section and profiled cross-section will be different on account of differing hydraulic diameters owing to the shape of the channels. This coefficient "h" can be found from the Nusselt correlation for each channel.

Hydraulic diameter for PCCC:

$$\text{Hydraulic Diameter} = D_H = \frac{4 \text{ x Cross-sectional area}}{\text{Wetted perimeter}}$$

Area of cross-section of PCCC = 78.5 mm^2

Perimeter = 38.7 mm

$$\text{Hydraulic Diameter (PCCC)} = \frac{4 \times 78.5}{38.7} = 8.1 \text{ mm} = 0.0081 \text{ m}$$

Reynolds Number for CCC

$$Re = \frac{\rho V D}{\mu}$$

Re = 10604

Reynolds Number for PCCC

Re = 8590

As the value of Reynolds number is greater than 3000, the flow in the channels is taken to be fully developed turbulent flow.

Convective Heat Transfer Coefficient "h"

Thermal conductivity of water = k = 0.615 W/m^{o}C

Prandtl's Number (Pr) = 5.42

Diameter = 0.01 m

For CCCC:

$$h = \frac{k}{D}\ 0.027\ \left[(Re_D)^{0.8} \times (Pr)^{0.33}\right]$$

h = 4799 W/m^{o}C (CCCC)

For PCCC:

$$h = \frac{k}{D_H}\ 0.027\left[\left(Re_{D_H}\right)^{0.8} \times (Pr)^{0.33}\right]$$

h = 5005 W/m^{o}C (PCCC)

As the diameter or hydraulic diameter decreases, the diffusion distance for heat convection decreases. This implies that heat flows more easily when the heat diffusion distance is less.

In other words, for the same velocity, a smaller passage has a higher convective heat transfer coefficient. PCCC has a lower hydraulic diameter as compared to CCCC (for the same cross-sectional area), therefore its "h" is higher as seen above.

3.8 Vertical Injection Moulding Machine

The Vertical Injection Moulding (VIM) machine that was used for injection moulding experiments has following dimensions for the mould to be used in the machine.

- Height 150 mm
- Width 150 mm
- Length 250 mm

The aluminium frame and the Epoxy mould design were done according to the sizes that could be installed in the VIM shown in Figure 3.13.

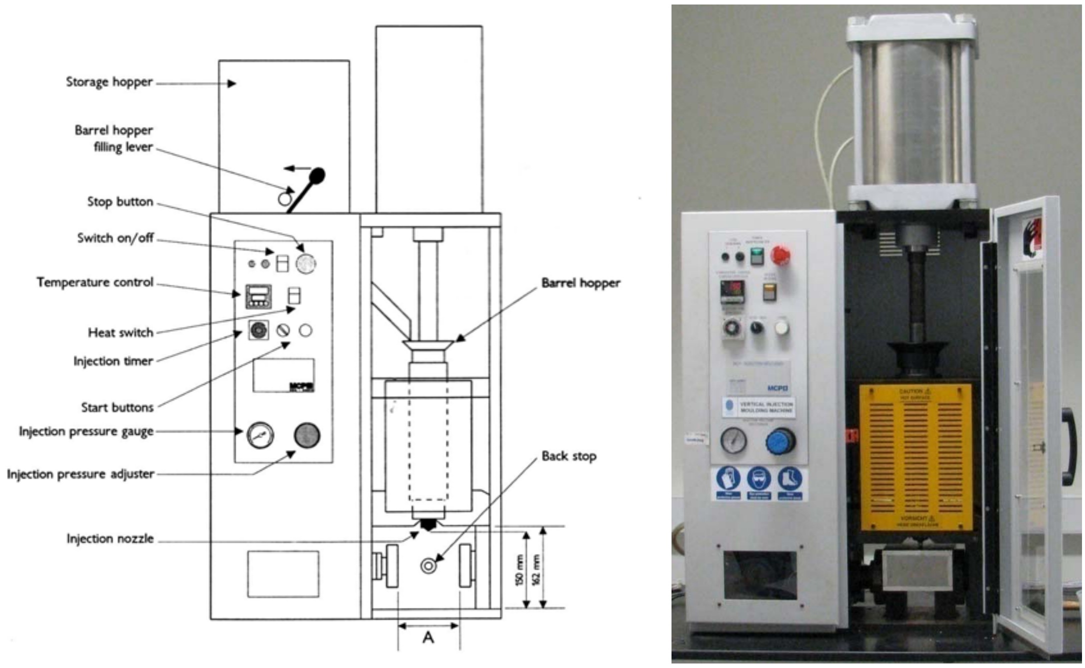


Figure 3.13 Vertical Injection Moulding Machine MTT Model 100KSA

<u>Technical Specifications of 100KSA</u>

Injection volume / shot weight		100 ml / 100 gm
Heating capacity		1.8 kW
Temperature range		20 – 350°C
Plasticising		7.0 kg/hr
Air line pressure		8 bar max.
Air consumption per cycle		96 litres
Effective stroke of plunger		195 mm
Standard plunger	diameter	35 mm
	Injection pressure air supply	8 bar
Locking force at 8 bar		20 tonnes
Locking clamp movement		5 mm

3.8.1 Aluminium Frame

To withstand the clamping force of the injection moulding machine, aluminium frames were needed for Epoxy moulds. For that reason, a customized frame was designed with aluminium plates of thickness ⅜ in (≈9.5 mm). The designed frame is shown in Figure 3.14 with the following dimensions.

Height	85 mm
Width	145 mm
Length	160 mm

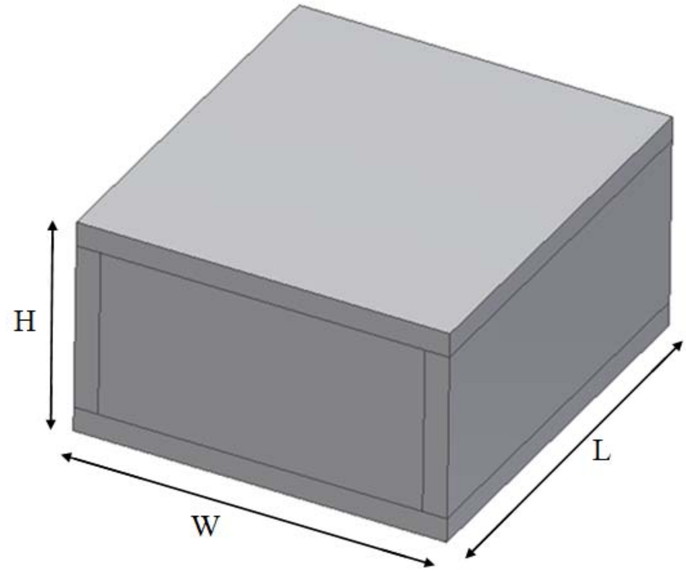


Figure 3.14 Aluminium Frame

The front and back plates of the frame could be removed for the provision of cooling pipe attachment. These frames were to be used in the casting of mould cavity block with the aluminium filled epoxy. The aluminium frame is shown in Figure 3.14.

3.9 Design of Mould Cavities for Fabrication

The design and modelling of mould cavity and cooling channels was done using solid modelling software as shown earlier in Figure 3.9 and Figure 3.10 for the CCCC and PCCC respectively.

The mould cavity was modelled into top and bottom sections. This was done owing to the complex shape of channels and modelling their layout profile in the mould cavities. The CAD solid model was also used for thermal simulation using FEA software as done previously.

The dimensions for mould cavity are given below.

Height	50 mm
Width	125 mm
Length	140 mm

The diameter for the circular channel was chosen as 10 mm with a cross sectional area of 78.5 mm^2.

3.9.1 Design of the Core for the Moulds

The core for the mould was designed so that it forms the moulded part cavity. The core design is shown in Figure 3.15.

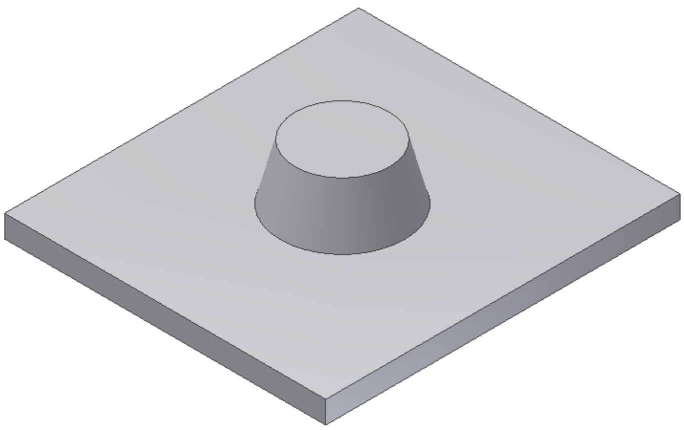


Figure 3.15 Mould Core

3.10 Design and Modelling of Patterns

From the solid models of RP patterns designed earlier for the channel and moulded part, 3D models were generated as exact counterparts of the mould, in terms of dimensions, location with respect to the cavity and position with respect to the base.

The wax patterns were produced with Thermojet Solid Object printer shown in Figure 2.5. The CAD models for CCCC and PCCC mould patterns are illustrated in Figures 3.16 and 3.17.

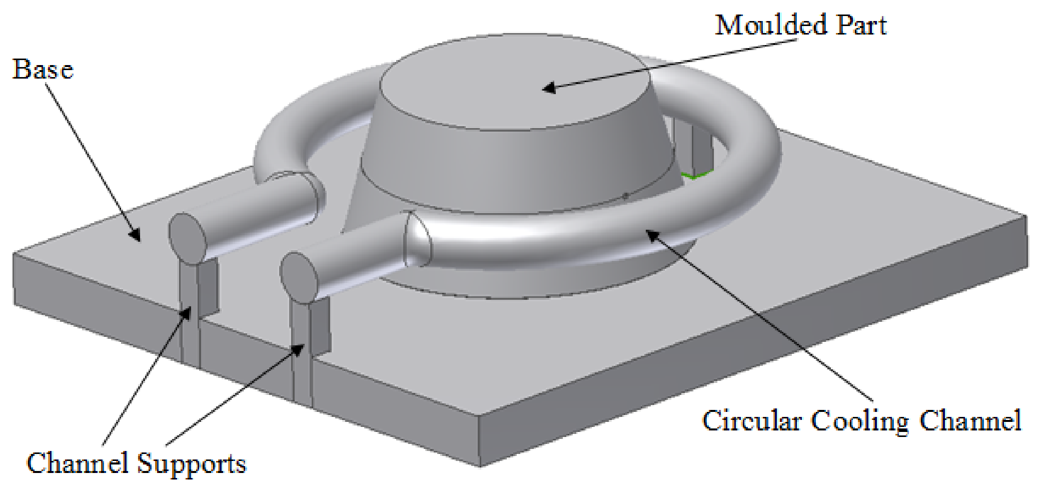


Figure 3.16 Circular Conformal Cooling Channel Pattern Assembly

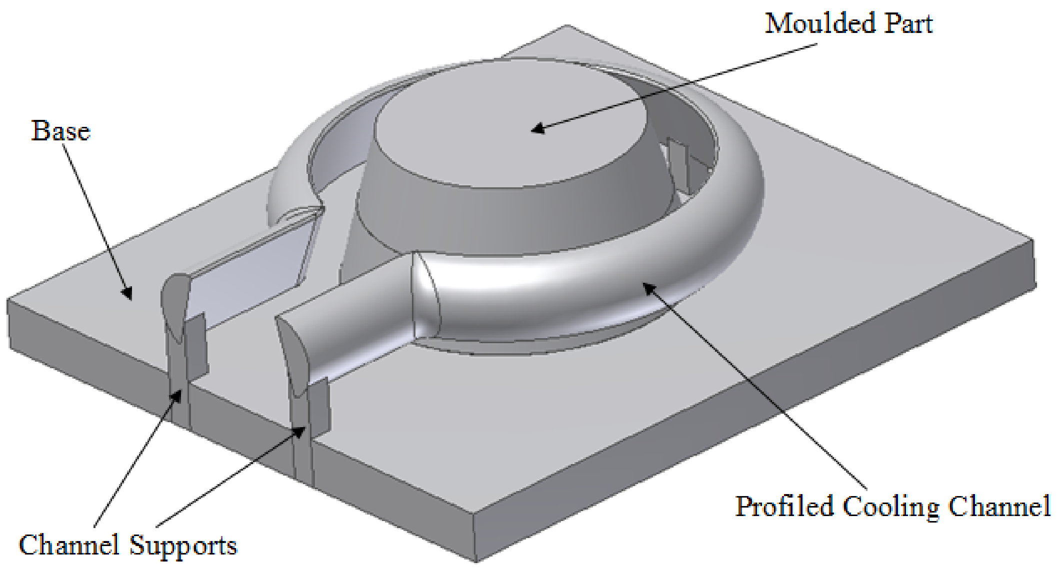


Figure 3.17 Profiled Conformal Cooling Channel Pattern Assembly

3.11 Fabrication of Mould Cavities with Epoxy

3.11.1 Epoxy Casting of Mould Cavities

The patterns of cavity and channel were placed in the aluminium frames for casting with epoxy and are shown in Figures 3.18 and 3.19.

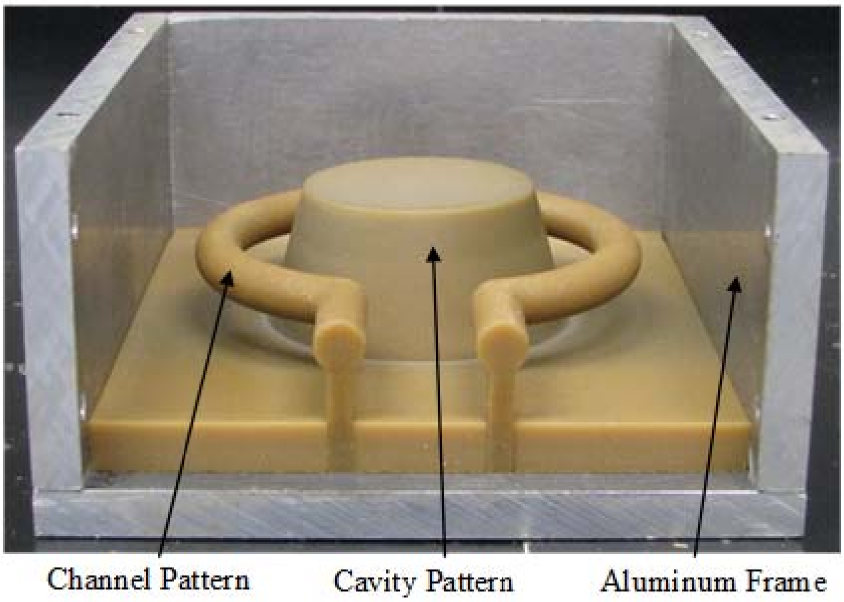


Figure 3.18 Circular Conformal Cooling Channel Pattern Assembly inside Casting Frame

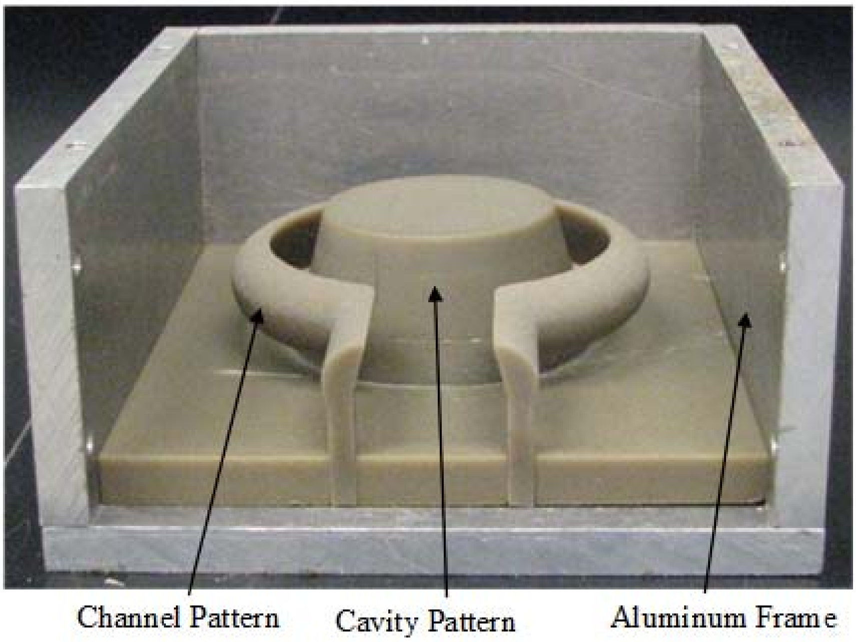


Figure 3.19 Profiled Conformal Cooling Channel pattern assembly inside the casting frame

Aluminium filled epoxy resin (Global-cast) was used for producing injection mould cavities and core. Epoxy was poured in a bucket and weighed according to the volume of casting frame minus the volume of pattern shown in Figure 3.20. An epoxy-hardener mixture at a ratio of 10:1 was prepared inside the bucket with a steel mixer and de-gassed in a vacuum chamber for 12 – 15 minutes [31] shown in Figure 3.21 according to the information provided with epoxy material.

Figure 3.20 Global-cast Epoxy weighed on the scale

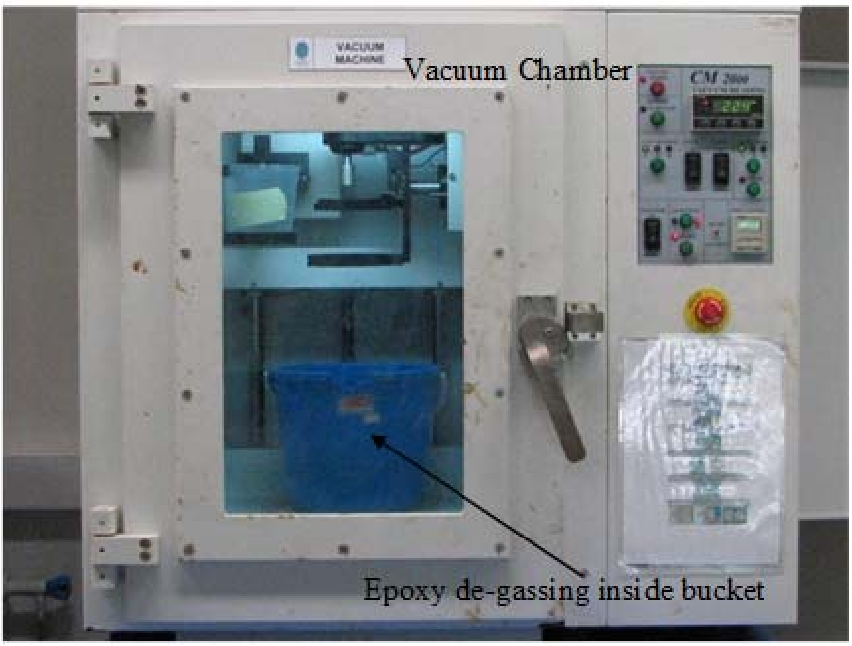


Figure 3.21 Epoxy being De-gassed inside the Vacuum Chamber

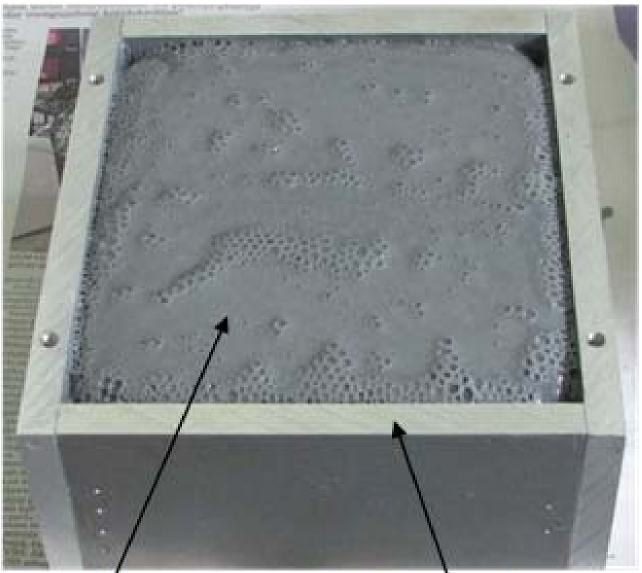


Figure 3.22 Epoxy cast in the aluminium frame

After de-gassing, the epoxy was poured onto the pattern inside the aluminium frame to cover the pattern assembly shown in Figure 3.22. The epoxy was cured as recommended for Global Cast epoxy.

The cure cycle was done in the oven. The final cure cycle temperature is 130^{o}C (section 3.13.3). During this cure cycle, the wax pattern which has melting temperature of 80^{o}C, was completely melted out from epoxy leaving the cavity and cooling channels in the mould. The square holes left by the channel supports were plugged with a commercially available epoxy compound. The curing of the epoxy moulds was also regarded as post processing for moulds,

3.11.2 Epoxy Casting of Mould Core

The fabrication of the core for the cavity was also done with Thermojet wax. The wax mould was designed and RP pattern was produced shown in Figure 3.23. Epoxy was poured in the pattern and after curing, the mould core was formed (Figure 3.24).

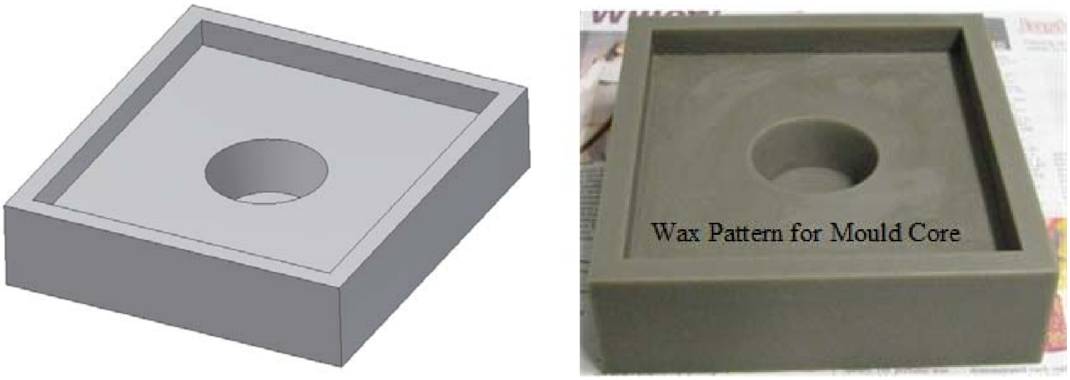


Figure 3.23 CAD model and Thermojet wax Pattern for Mould Core

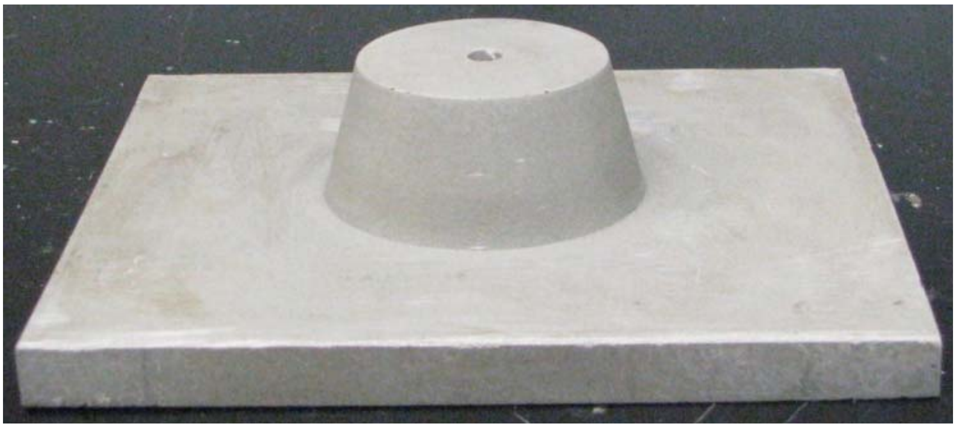
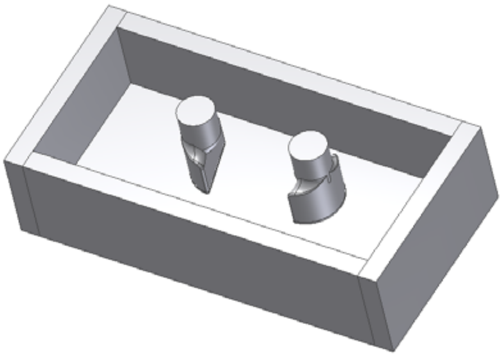


Figure 3.24 Epoxy Core

3.12 Cooling pipes Attachment Fabrication

The cooling water tubes were connected to the circular channel mould through brass nozzles. The brass nozzles for the attachment of cooling pipes cannot be fitted with the profiled shape channels due to their non-circular shape. For connecting the pipes with the profiled channel mould, an interface structure had to be designed as in Figure 3.25 with one end profiled, the other being circular. The pattern for the epoxy casting was made with Thermojet solid object printer. Epoxy was poured and after curing, the profiled barb attachment was formed (Figure 3.26). The attachment was bolted with the profiled channel mould cavity shown in Figure 3.27.



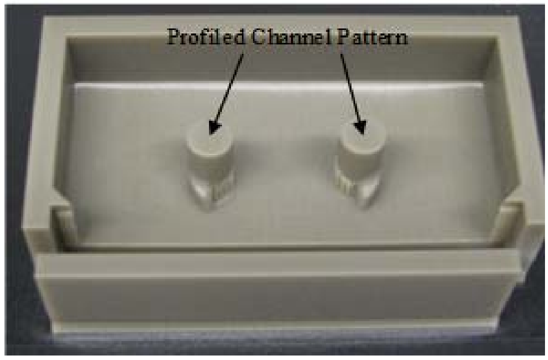
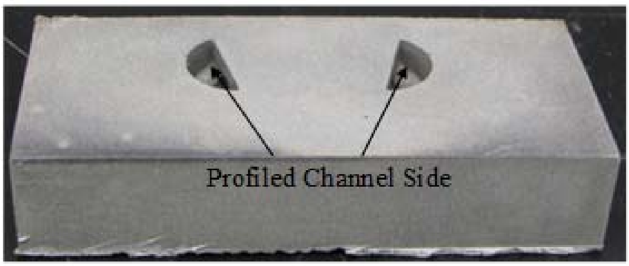


Figure 3.25 CAD model and Thermojet wax pattern for Profiled Channel Interface



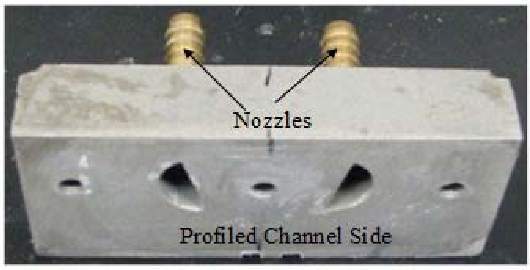


Figure 3.26 Cast and machined part with nozzles

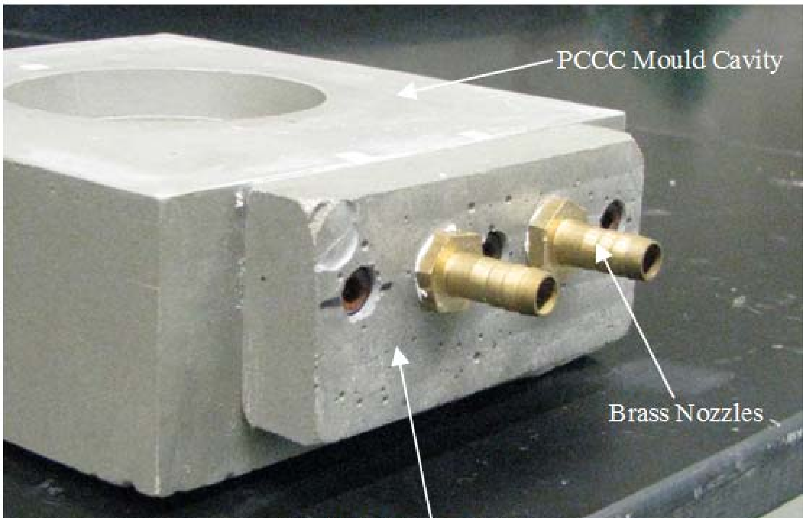


Figure 3.27 Profiled Channel Interface bolted with PCCC Mould Cavity

The epoxy mould cavities with circular and profiled conformal channels were fabricated with Global-cast aluminium-filled epoxy. These mould cavities are shown in Figure 3.28.

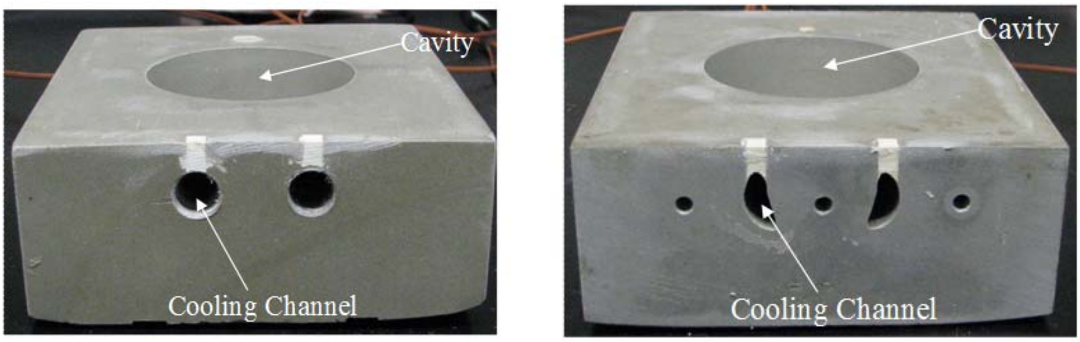


Figure 3.28 Circular and Profiled Conformal Cooling channel Mould Cavities

One mould cavity each for CCCC and PCCC were sectioned so as to show the circular and profiled channels inside the mould cavities. The sectioned views for these can be seen in Figures 3.29 and 3.30.

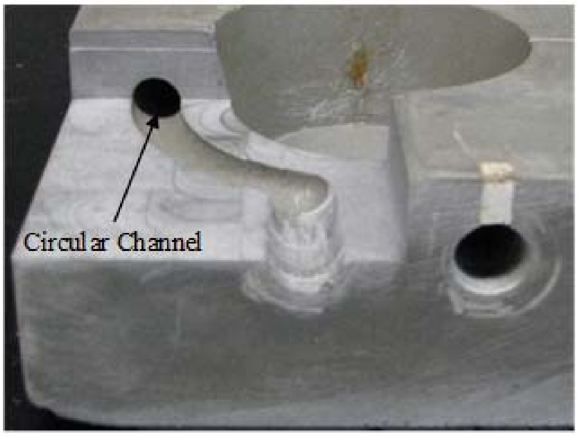


Figure 3.29 Cut away sections of Circular Conformal Channel Mould

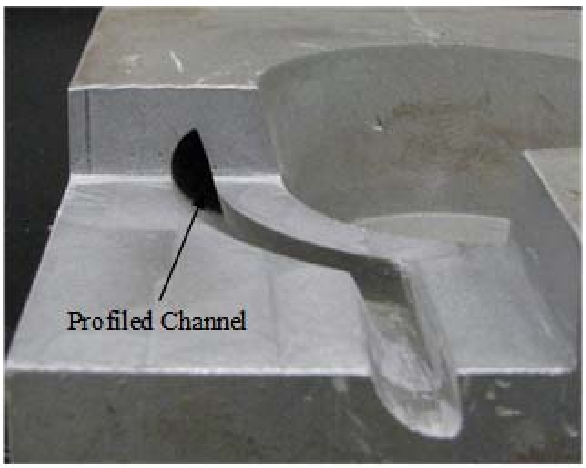


Figure 3.30 Cut away sections of Profiled Conformal Channel Mould

3.13 Globalcast Properties

Mixing Ratio	Parts by Weight
Globalcast HT 133A (epoxy)	100
Globalcast HT 130-3B (hardener)	10

3.13.1 Properties before Curing

<u>Globalcast HT 133A (epoxy)</u>	
Viscosity	30,000 – 70,000 cps
Density	1.5 – 1.55 gm/cm^3
<u>Globalcast HT 130-3B (hardener)</u>	
Viscosity	110 – 150 cps
Density	1.01 – 1.05 gm/cm^3

3.13.2 Properties after Curing

Compressive Strength	115 – 125 Mpa
Flexural Strength	65 – 75 Mpa
Specific gravity	1.55 – 1.65 gm/cm^3
Martens heat distortion temperature	130 – 135 ^{o}C
Linear shrinkage	0.02- 0.06 mm
Thermal conductivity	0.6 – 0.7 W/m.K
Hardness	85 – 90 Shore D

3.13.3 Cure Cycle

Temperature	Duration
25^{o}C	24 Hours
60^{o}C	4 Hours
100^{o}C	2 Hours
130^{o}C	12 Hours

Volume of part 31.75 cm^3

Weight of part 33.5 gm

The properties of the epoxy and the cure cycle were provided by the material manufacturer along with the material. The cure cycle was done by placing the epoxy mould inside the oven for the recommended time period. Please refer section 3.13.3, recommended cure cycle for aluminium filled epoxy.

3.14 Fabrication of Mould Cavities with Embedded Thermocouples for Temperature Measurement

For the measurement of moulded part temperature during the part cooling process, thermocouples needed to be placed within the mould cavities with circular and profiled channels. The technique used was to embed the thermocouple inside the mould cavity during the epoxy casting process itself. Two thermocouples each are embedded in such a way that the thermocouples bead is at the centre plane of the mould cavity as shown in Figure 3.31.

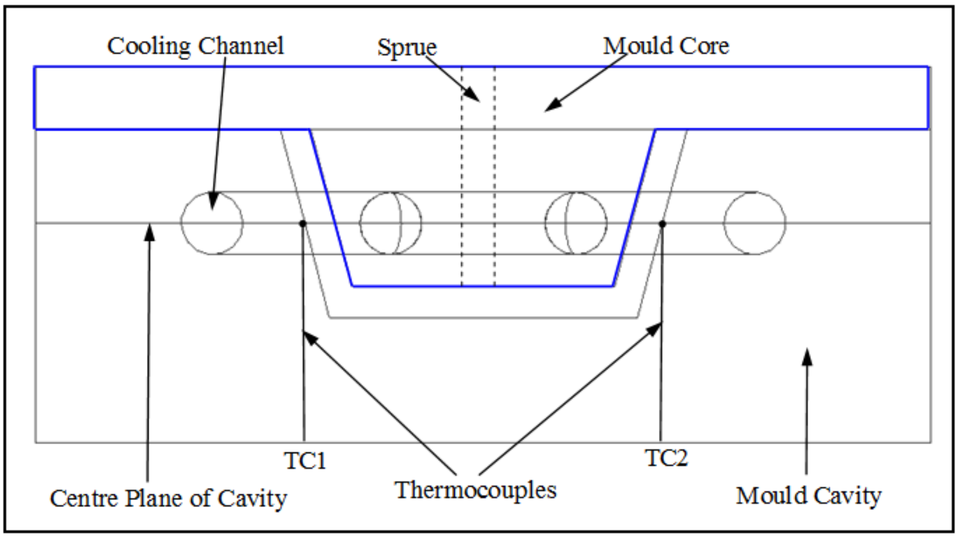


Figure 3.31 Thermocouple Placement in the Mould

The position for the centre plane on the part pattern were measured and marked. The thermocouples were passed through the thermocouple holder fabricated with Thermojet 3D printing RP process shown in Figure 3.32. Thermocouples positioning and placement is shown in Figures 3.31 and 3.32.

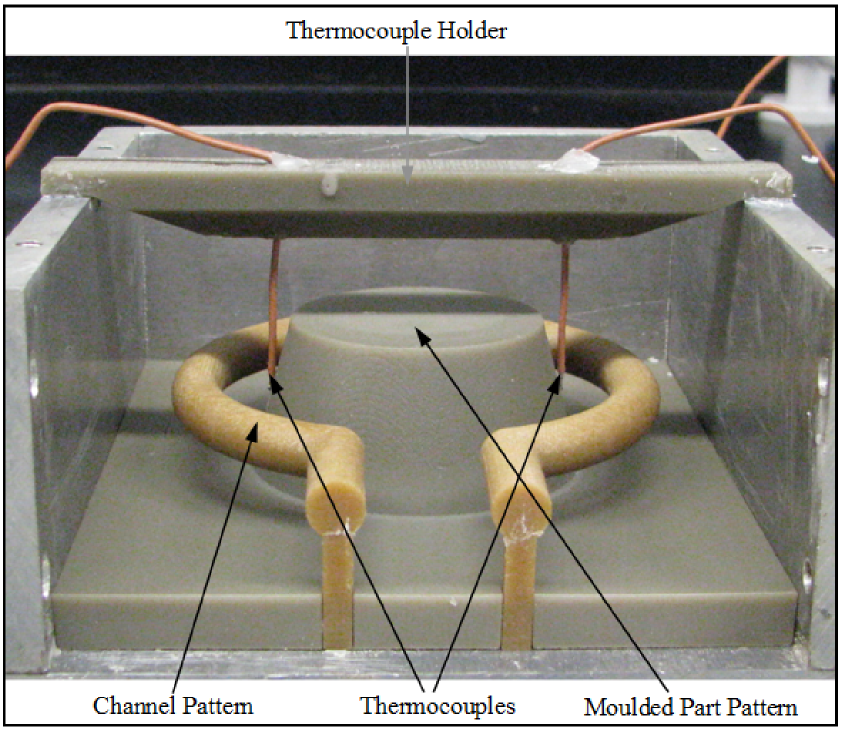


Figure 3.32 Patterns with Thermocouples

The pattern assembly with thermocouples was placed inside the aluminium frame for epoxy casting. The same epoxy casting procedure was repeated as done earlier for the fabrication of CCCC and PCCC mould cavities.

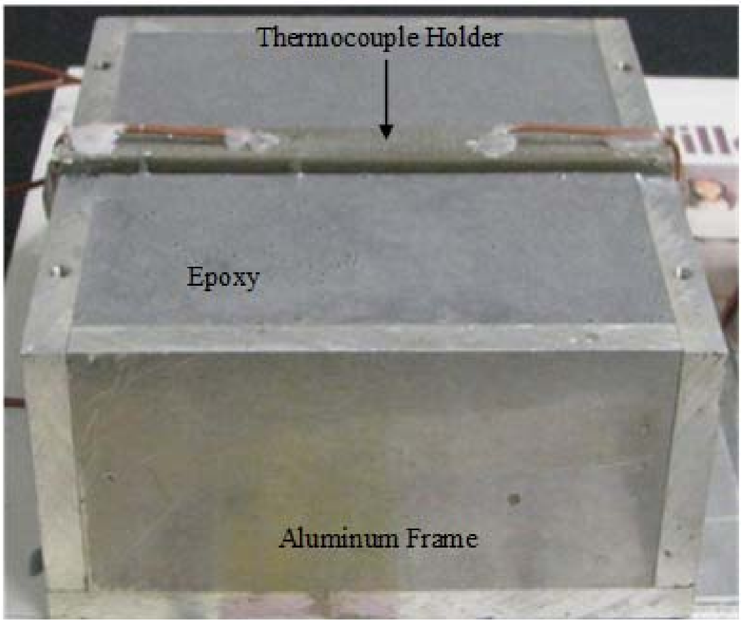


Figure 3.33 Epoxy cast in the aluminium frame with Thermocouples

The epoxy was poured onto the pattern and thermocouples inside the aluminium frame to cover the assembly shown in Figure 3.33. The same cure cycle was repeated as done earlier and after the cure cycle, thermocouples were embedded in the mould cavity shown in Figure 3.34. The complete mould cavities with thermocouples and cooling pipe connectors can be seen in Figure 3.35.

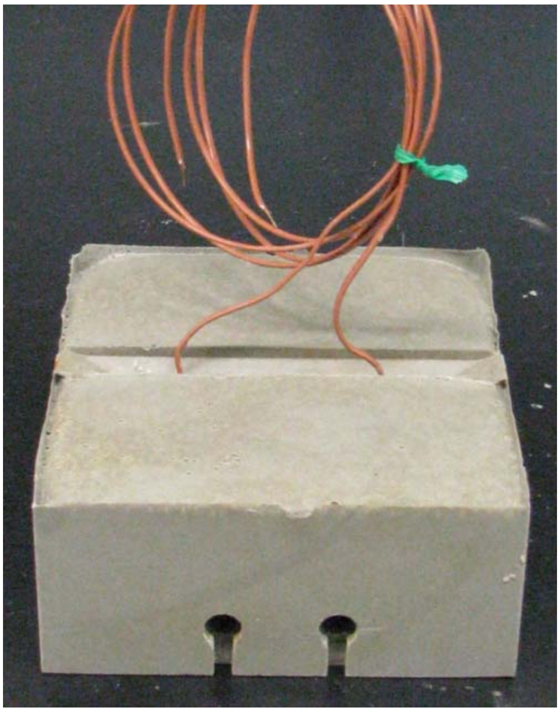


Figure 3.34 Epoxy Mould Cavity with Embedded Thermocouples

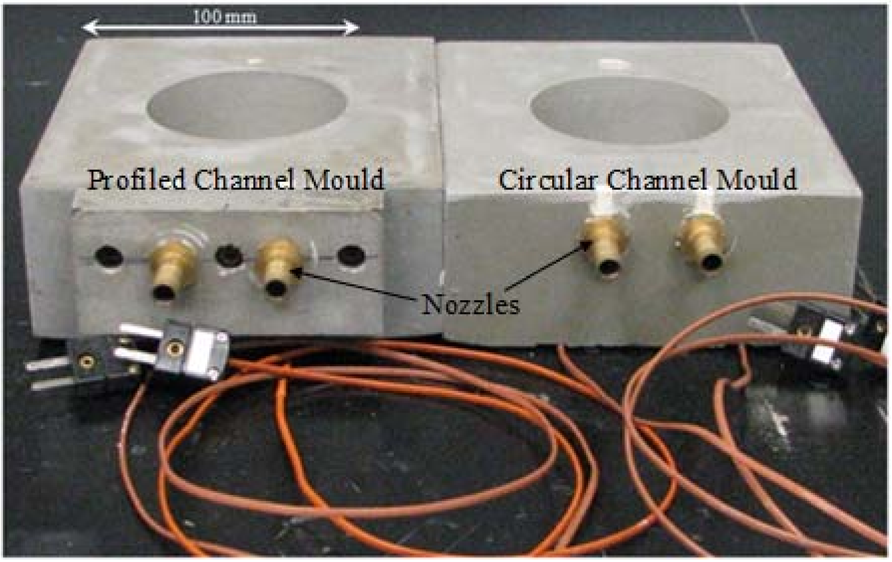


Figure 3.35 Epoxy Mould Cavities with Thermocouples and Cooling Pipe Connectors

3.14.1 Fabrication of Cooling Fluid Temperature Measurement Attachment

For the purpose of temperature measurement for cooling fluid flowing during the injection moulding process an attachment had to be fabricated with a thermocouple fitted for temperature recording.

For the attachment fabrication, a brass tee of size $^5/_8$ inch was utilized as the basic structure. A thermocouple was inserted in the perpendicular hole of the tee and then it was sealed using a commercial epoxy compound. The attachment images are shown in Figures 3.36 and 3.37. The flow meter and fluid temperature attachment connected with the mould are shown in Figure 3.38.

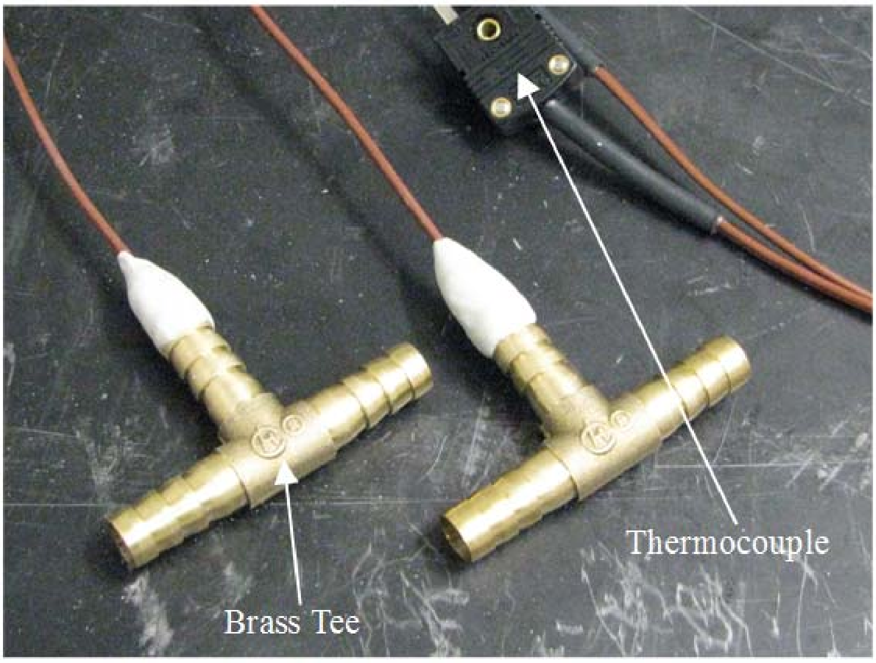


Figure 3.36 Cooling Fluid Temperature Measurement Attachment

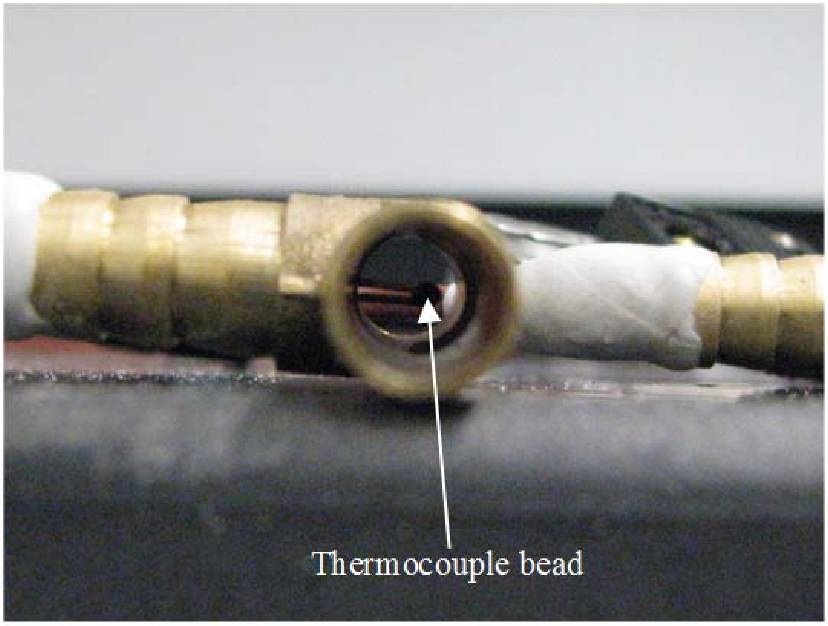


Figure 3.37 Cooling Fluid Temperature Measurement Attachment

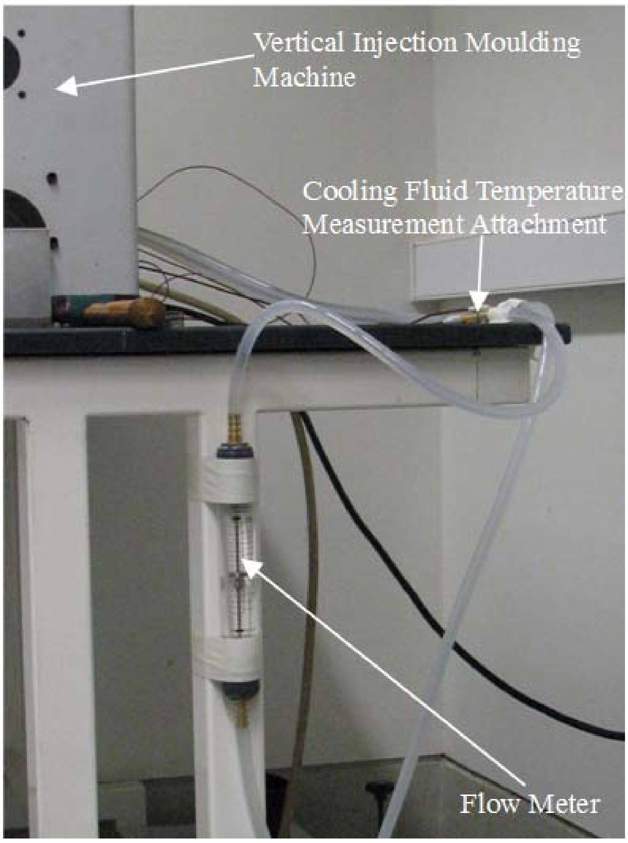


Figure 3.38 Cooling System for Moulds

3.15 Mould Cooling and Cycle Time

For achieving high production rates in injection moulding, fast mould cooling is needed as cooling time represents a major part of the total cycle time. Inappropriate cooling rate in injection moulding can result in deformation of the polymer parts, if ejected while still soft. Inadequately designed cooling channels can also result in part warpage due to uneven cooling.

Rees [51] indicated some of the most important factors that influence the cooling of a mould listed below.

- Cooling channels (layout, size) in the components in contact with the moulded product.
- Flow of coolant
- Thermal conductivity of mould parts
- Chemical composition of the coolant.
- Temperature increase (ΔT) of the coolant from inlet to outlet.

The heat contained in the molten plastic is transferred to the mould cavity, and it has to be removed so that the plastic can return to its solid form before ejection. The heat removal takes place mostly through the cooling medium.

3.16 Thermal Conductivity of the Mould Material

The thermal conductivity of the mould material is one of the important factors in the overall injection moulding process. The thermal conductivity of the material directly relates to the cooling of the mould and hence to the productivity of the IM process.

The mould material used for the current research was an aluminium powder filled epoxy. This material has a thermal conductivity which generally ranges from 0.6 – 0.7 W/mK. The aluminium particles are mixed with epoxy to increase the thermal conductivity of epoxy. But even in the case of aluminium filled epoxy, the thermal conductivity is very low as compared to moulds fabricated with metals. The thermal conductivities of aluminium filled epoxy and some metals generally used for the manufacturing of injection moulds are given in the Table 3.1 below.

Table 3.1 Thermal Conductivity of some materials

Material	Thermal Conductivity (W/mK
Aluminium	237
Beryllium Copper	130
Tool Steel H13	28.6
Aluminium Filled Epoxy	0.6 – 0.7
Plain Epoxy	0.2

This disadvantage of low thermal conductivity can be an issue in the moulds fabricated with epoxy as the cooling time is still quite high as compared to metal moulds. If the thermal conductivity of epoxy can be improved, we can get the maximum advantages of rapid tooling techniques for injection moulding process. Hence, another idea was contemplated of embedding thermally conducting metal inserts within the epoxy moulds to enhance the thermal conductivity of moulds made with epoxy in order to further reduce the cooling time for the polymer part.

3.17 Metal Inserts in Epoxy Moulds

The heat from the molten plastic is transferred to the mould cavity, and is removed mostly through the cooling medium. The heat travels from the melted plastic part into the mould material towards the cooling channel where it is taken away by the cooling fluid. The heat flow in the epoxy is slow due to the low thermal conductivity. If a high conducting metal medium is placed within the heat flow lines, the heat will travel faster through the metal and reach the channel in a shorter time. Metal inserts made from aluminium alloy were embedded between the mould cavity and the cooling channel for both CCCC and PCCC moulds. Aluminium was selected as the insert material because of its high thermal conductivity.

3.17.1 Insert Design

The insert is designed so that it seats on the cavity pattern exactly at the centre line of the cavity and cooling channel. Insert dimensions are as follows for CCCC and PCCC moulds. Insert design are shown in Figure 3.39 and Figure 3.40 for CCCC and PCCC moulds respectively. The insert dimensions are selected so that the insert can occupy the maximum space between the cavity and the cooling channel (Figure 3.41 and 3.42). The ring thickness is 10 mm same as the diameter for circular channel. The insert is circular in shape as the cavity is circular.

3.17.1.1 Insert Dimensions CCCC Mould

- Inner Diameter = 60.7 mm
- Outer Diameter = 78 mm
- Thickness = 10 mm

3.17.1.2 Insert Dimensions PCCC Mould

- Inner Diameter = 60.7 mm
- Outer Diameter = 75.3 mm
- Thickness = 10 mm

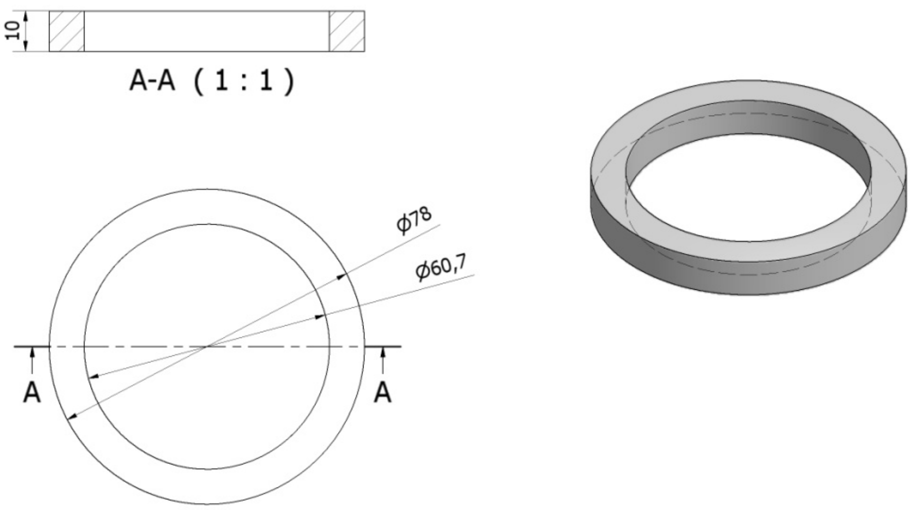


Figure 3.39 Aluminium Ring Insert for CCCC Mould

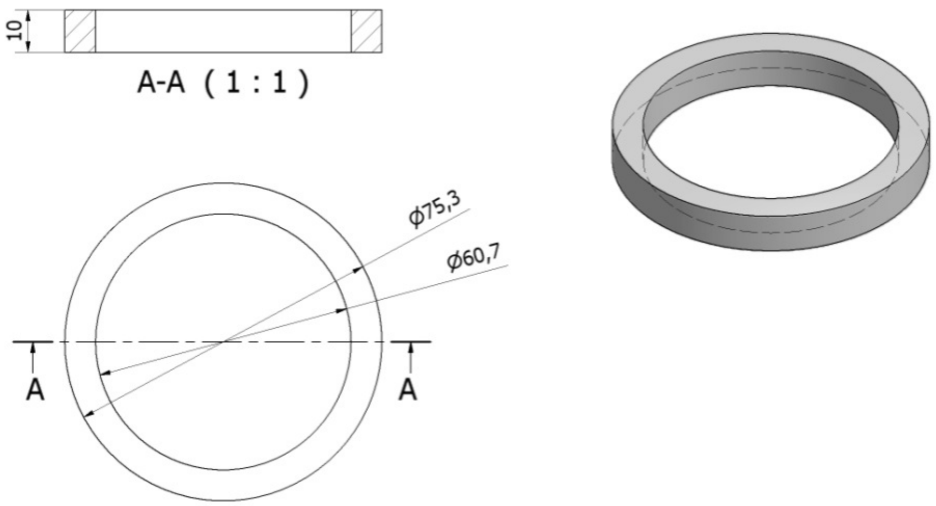


Figure 3.40 Aluminium Ring Insert for PCCC Mould

The ring shaped inserts were fabricated using 10 mm thick aluminium alloy plates. The inserts were cut according to the dimensions with the EDM wire cut machine.

3.18 Conducting Insert Placement with respect to Cavity and Channel Patterns

The inserts were placed for both CCCC and PCCC moulds on the cavity pattern. Figure 3.41 and 3.42 shows the placement of insert with the CCCC pattern. Figure 3.43 and 3.44 shows the placement of insert with the PCCC pattern.

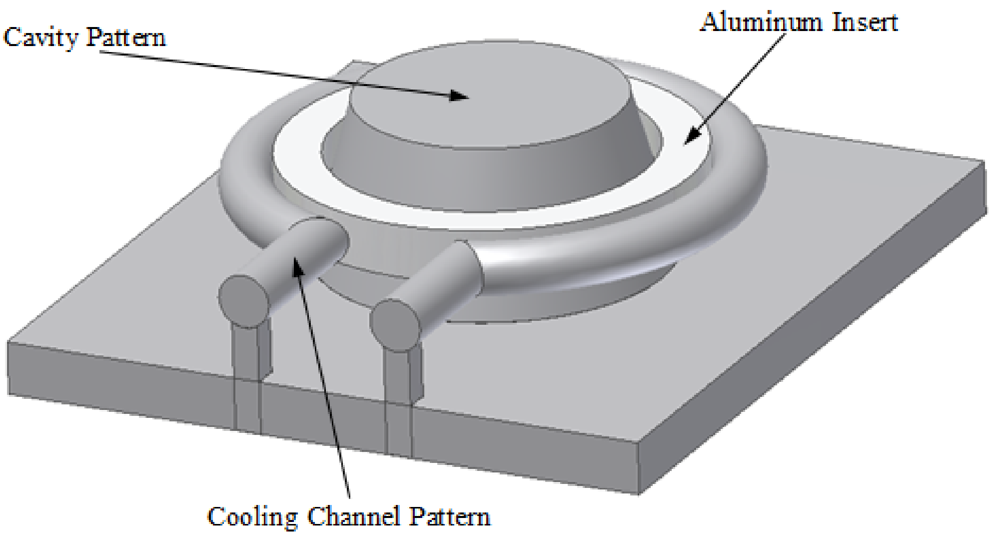


Figure 3.41 CCCC pattern with Conducting Insert

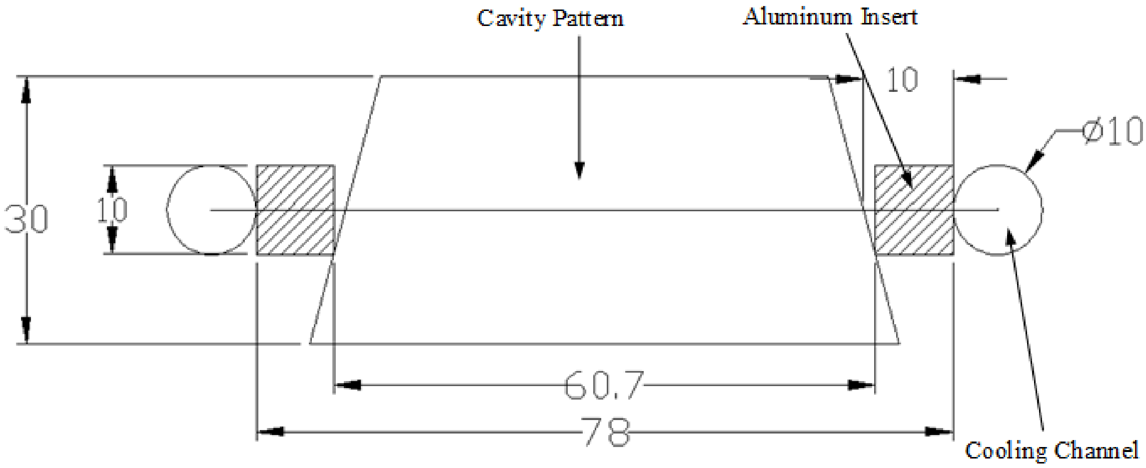


Figure 3.42 Insert Placement CCCC mould

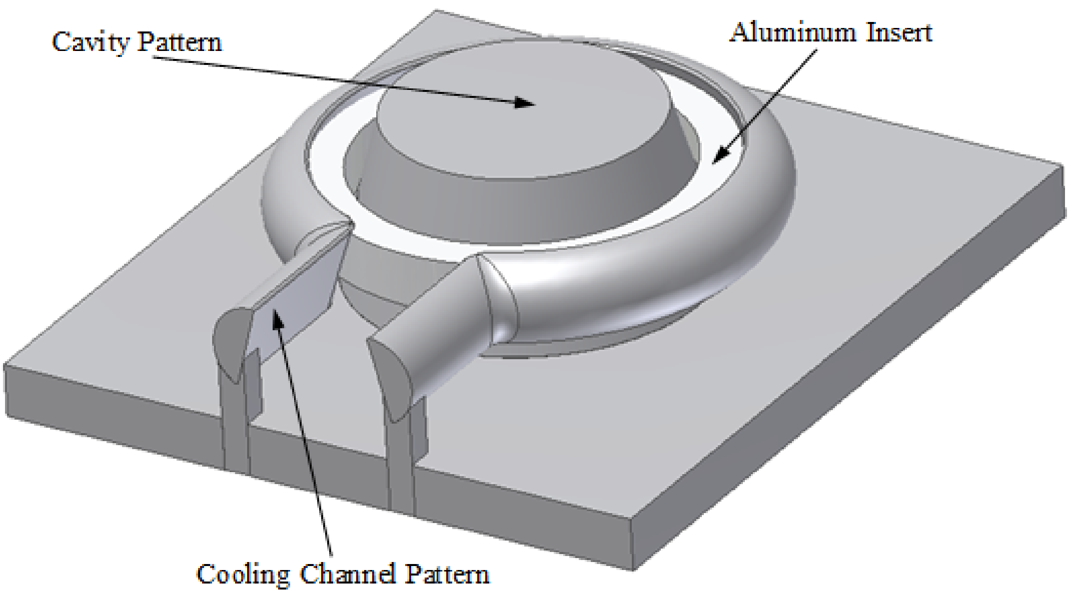


Figure 3.43 PCCC pattern with Conducting Insert

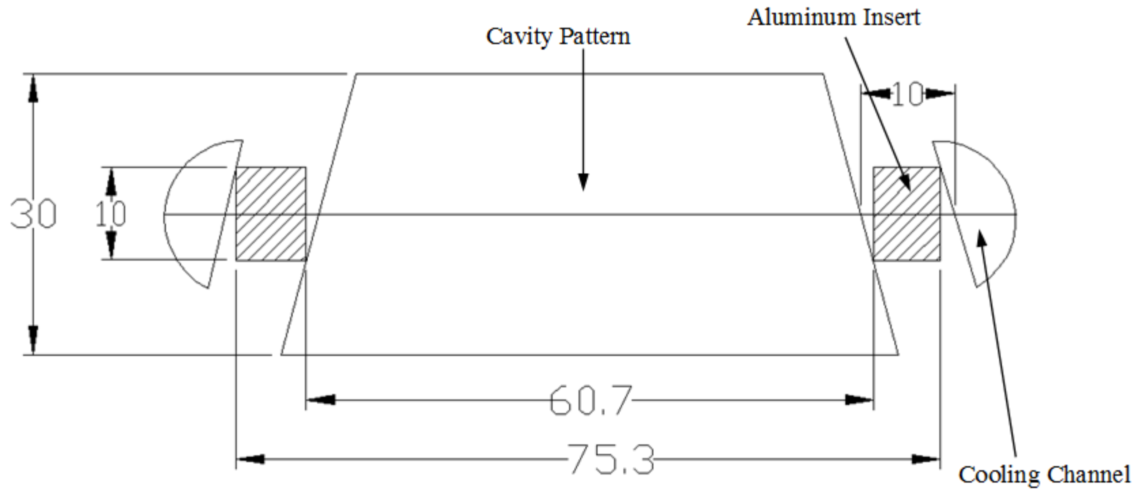


Figure 3.44 Insert Placement PCCC mould pattern

Figure 3.45 shows cross sections for CCCC and PCCC moulds with inserts.

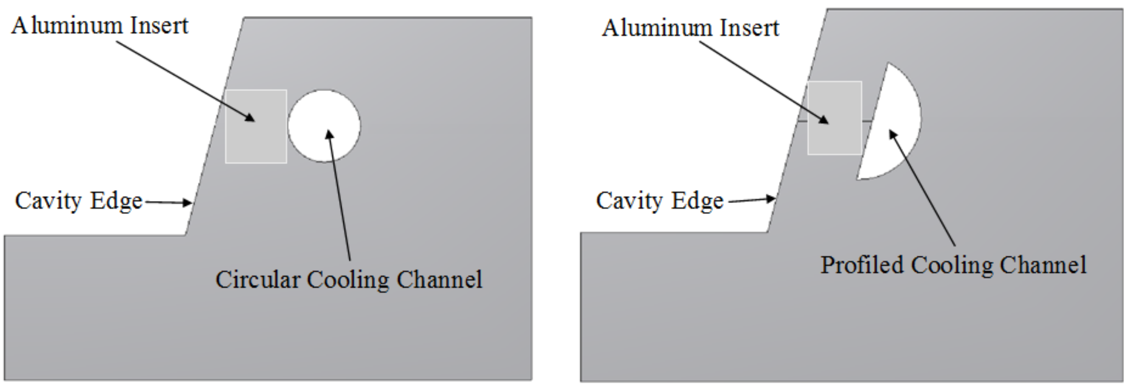


Figure 3.45 Insert placement for CCCC and PCCC moulds

3.19 Fabrication of Epoxy Moulds with Embedded Conducting Inserts and Thermocouples

The fabrication procedure for epoxy moulds with embedded conducting inserts was the same as done before and described previously in section 3.11.1.

The completed mould frame with patterns and aluminium insert is shown in Figure 3.46. For the measurement of moulded part temperature, thermocouples needed to be placed within the mould cavities with circular and profiled channels. The technique used for doing that was to embed the thermocouple inside the mould cavity during the epoxy casting process as described earlier. Two thermocouples each were embedded in such a way that the thermocouples bead was at the centre plane of the mould cavity. The positions for the centre plane on the part pattern were measured and marked. The thermocouples were passed through the thermocouple holder fabricated with Thermojet 3D printing process as shown in Figures 3.46 & 3.47.

Epoxy resin was used for making injection mould cavities with aluminium inserts. The core was the same as used with previous CCCC and PCCC moulds. Epoxy was poured in a bucket and weighed according to the volume and then epoxy-hardener mixture at a ratio of 10:1 was prepared inside the bucket with a steel mixer and de-gassed inside a vacuum chamber for 12 – 15 minutes [31] according to the information provided with epoxy material.

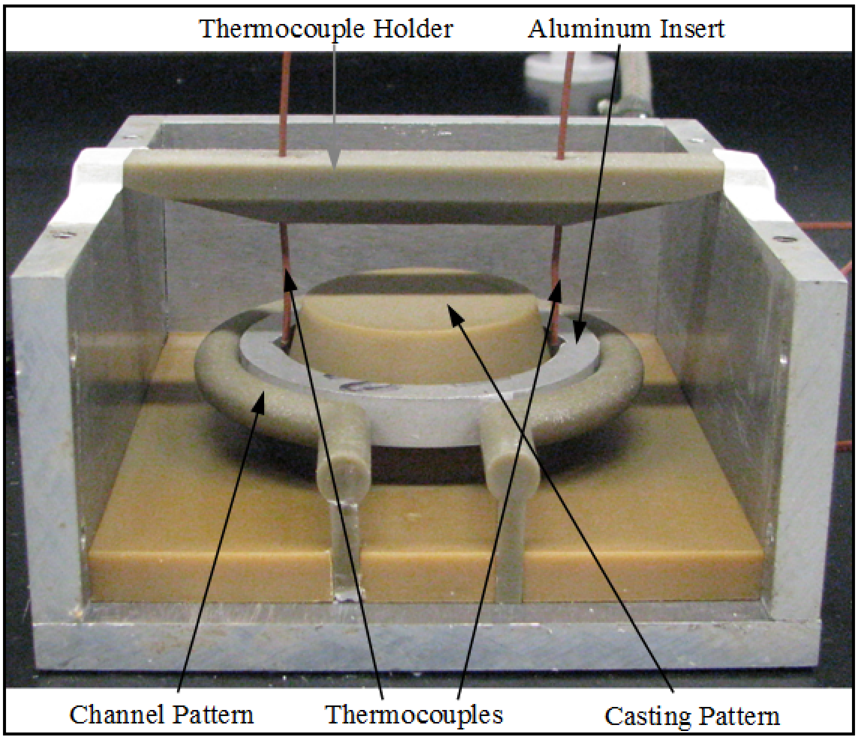


Figure 3.46 Thermocouple Placement CCCC Mould with Insert

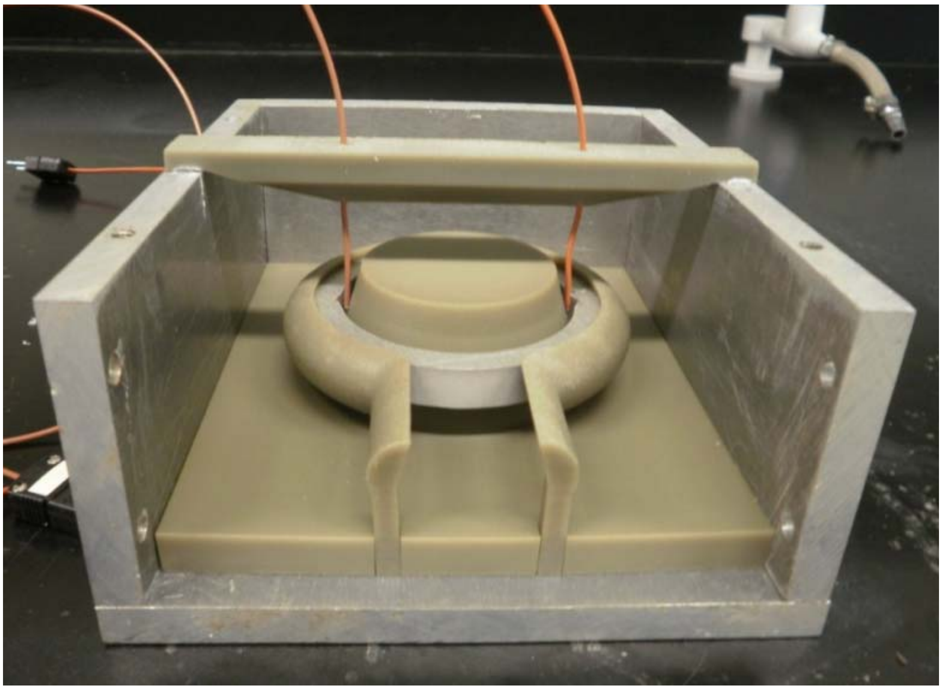


Figure 3.47 Thermocouple Placement PCCC Mould with Insert

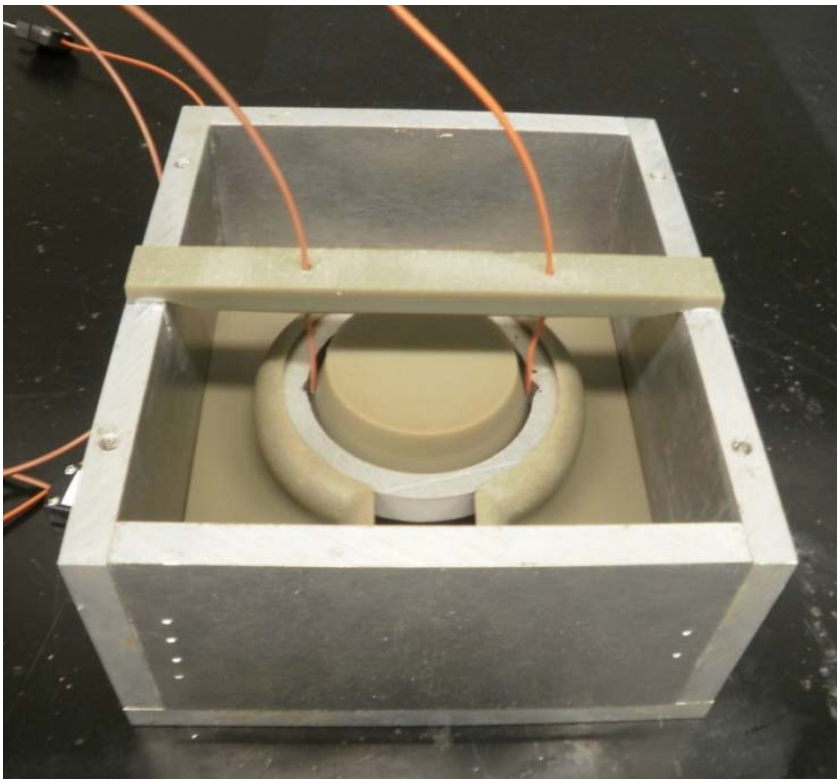


Figure 3.48 Mould Frame prepared for epoxy pouring

Figure 3.48 shows the prepared mould frame for epoxy pouring. After de-gassing, the epoxy was poured onto the pattern inside the aluminium frame to cover the pattern assembly as shown in Figure 3.49.

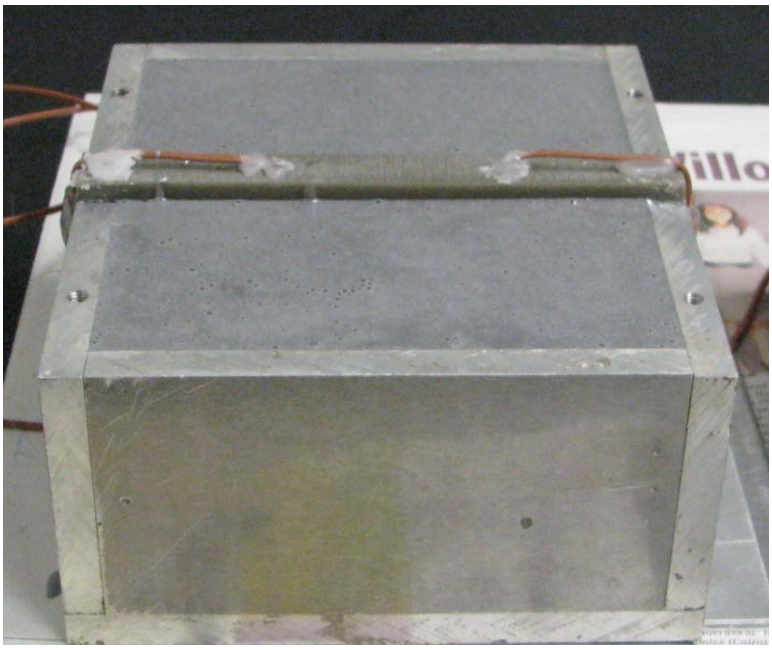


Figure 3.49 Mould frame with epoxy poured

During the cure cycle (section 3.13.3), the wax pattern was melted out from epoxy leaving the cavity, cooling channels and thermal insert embedded within the mould. The complete mould cavity is shown in Figure 3.50.

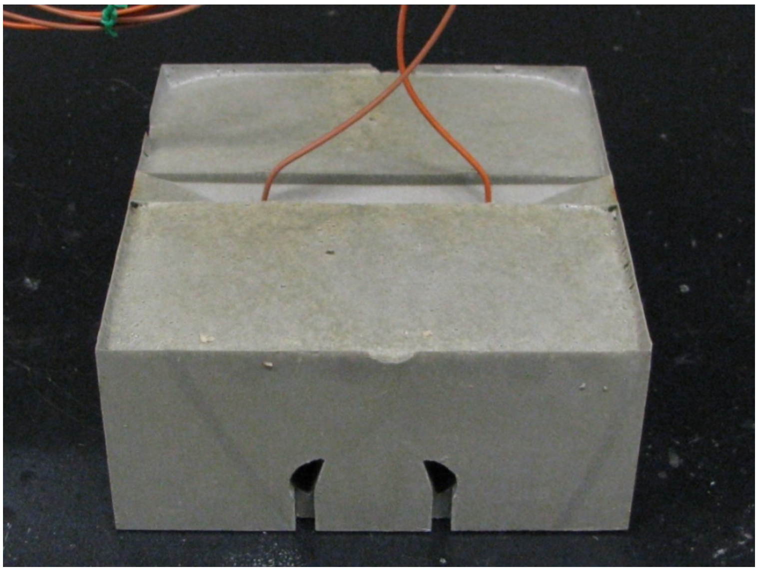


Figure 3.50 Prepared Epoxy Mould Cavity

3.20 Conformal Inserts with Straight Cooling Channels

Research on the concept of conformal cooling channels has confirmed that conformal cooling has better results than straight channels. The concept of conformal cooling channels (CCC) was also applied to current research of injection moulds fabricated with aluminium filled epoxy material. Profiled conformal cooling channels (PCCC) could give better heat dissipation than circular conformal cooling channels (CCCC) as described earlier in the chapter.

Another idea was also conceived for further studying the concept of metal inserts. This idea was to use a Conformal Insert instead of a circular ring shape insert. Either Straight circular or straight profiled channels can be used with the conformal insert. The straight channels have the advantage of using ready-made metal tubes that can be connected with water conveniently with barbed connectors.

The idea of conformal insert is shown in Figure 3.51 and the assembly for mould casting is shown in Figure 3.52.

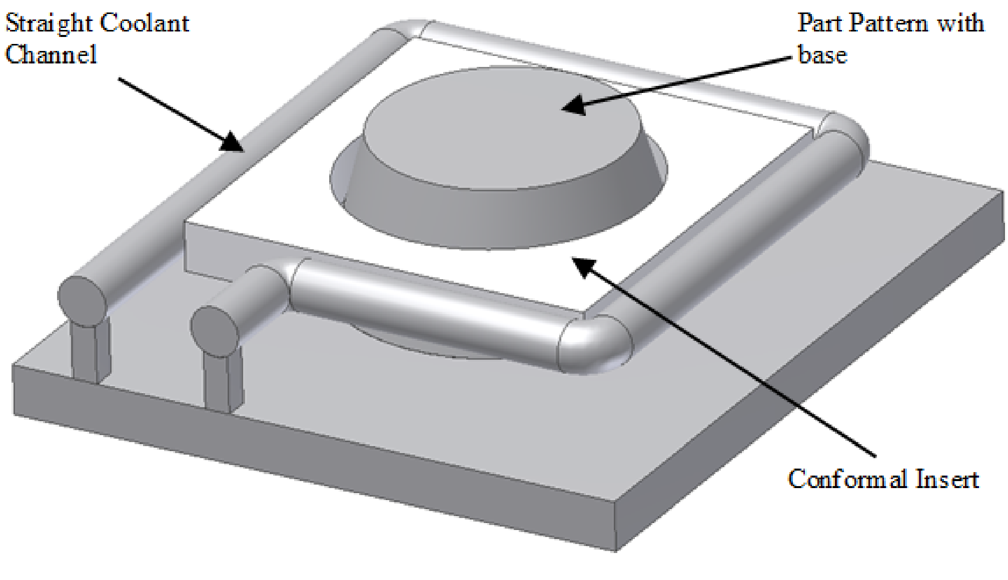


Figure 3.51 Conformal Insert with Straight channels and Pattern

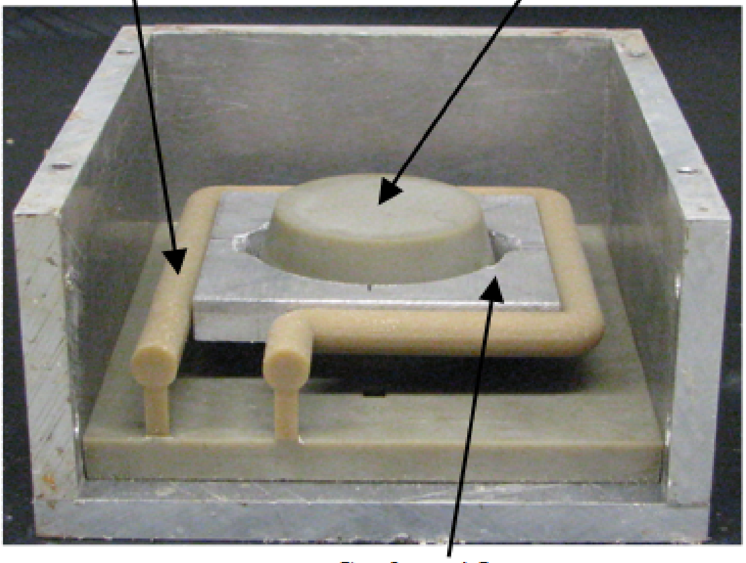


Figure 3.52 Conformal Insert with Straight channels and Pattern inside mould frame

The assembly ready for epoxy casting along with thermocouples for temperature measurement is shown in Figure 3.53.

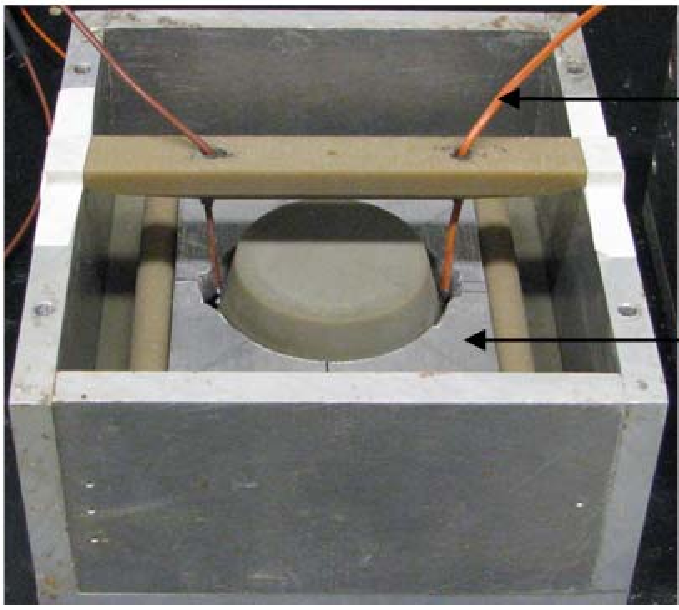


Figure 3.53: Complete Assembly with Thermocouples for Epoxy casting

The epoxy casting technique was done in the same way as before to get a mould frame with straight channels and a conformal insert embedded within the mould cavity.

3.21 Injection Moulding Experiments

3.21.1 Selection of Thermocouples

The thermocouples used for temperature measurement were type J thermocouples. These J type (Iron-constantan) thermocouples were selected as they have about 25% higher thermoelectric potential and hence higher accuracy when using the data logger.

3.21.2 Injection Moulding Experimental Procedure

For Injection Moulding experiments, the vertical injection moulding machine was used. The epoxy Injection mould insert with the aluminium frame was fixed in the IM machine. Thermocouples were used for temperature measurement of the moulded part. For recording temperature data, the data logger was used. For the measurement of cooling water flow, a flow meter with a flow range of 1 – 7 litres per minute was used.

3.21.3 Injection Moulding Parameters

Initial temperature before injection	31^{o}C
Ejection Temperature	35^{o}C
Injection Pressure	6 bar
Injection moulding machine temperature	190^{o}C
Injection Time	5.5 sec
Water Flow rate	4 litre/min
Moulding material	Polystyrene

3.21.4 Technique for Injection Moulding Experiments

Injection moulding was done with both circular conformal cooling channel (CCCC) and profiled conformal cooling channel (PCCC) moulds. Starting reference temperature for each run of injection was taken as 31^{o}C. IM machine pressure was set to 6 bar. Through the trial moulding run, the ejection temperature was determined as 35^{o}C. Temperatures were recorded at the following points.

- Thermocouple 1 TC1 Cavity Wall location 1
- Thermocouple 2 TC2 Cavity Wall location 2

TC1 and TC2 locations are shown in Figure 3.31.

- Thermocouple 3 TC3 Coolant inlet Temperature
- Thermocouple 4 TC4 Coolant outlet Temperature
- Thermocouple 5 TC5 Ambient Temperature

Reference temperature for injection and ejection were taken as 31^{o}C and 35^{o}C respectively taken from the initial experiment. Measurements were recorded from the reference temperatures and stored in the computer. The data was taken from the software and converted into graphical form.

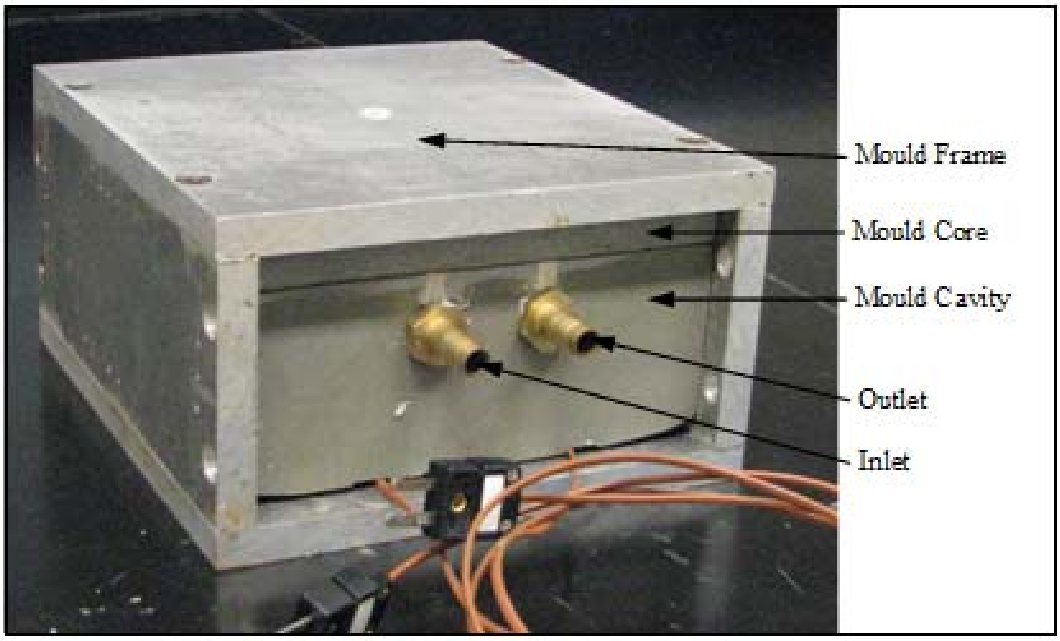


Figure 3.54: Complete Epoxy Mould Assembly with Aluminium Frame

Figure 3.54 shows the complete mould assembly used for the injection moulding experiments. Mould cavity and core were placed in the aluminium frame to be fitted in the vertical injection moulding machine. The mould assembly connected with cooling pipes and data logger is shown in Figure 3.55 and the experimental setup is shown in Figure 3.56.

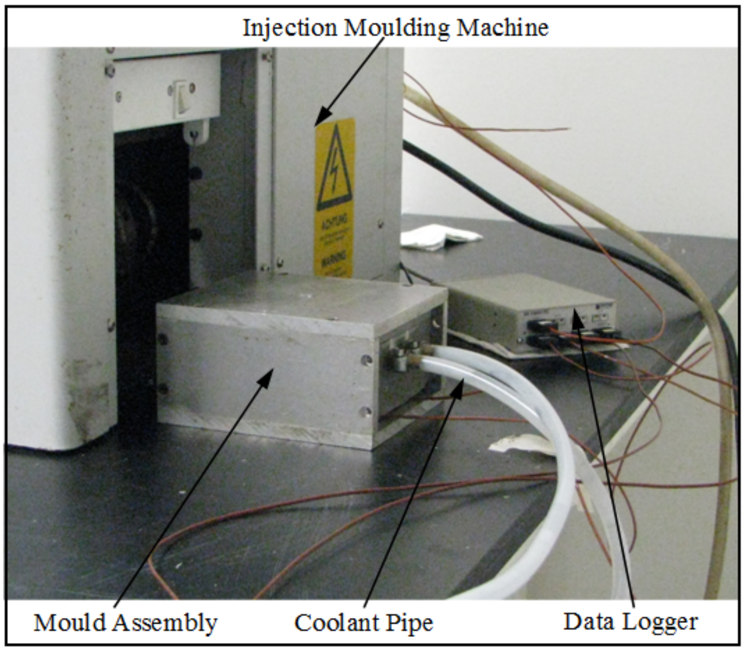


Figure 3.55 Mould attached with cooling pipes and Data Logger

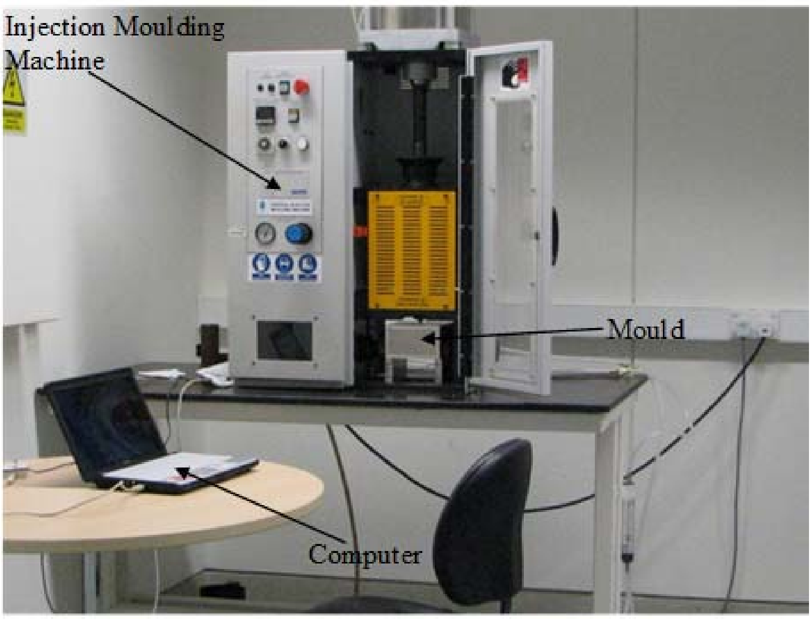


Figure 3.56 Experimental Setup

3.22 Summary

In this chapter, thermal analysis methodology and the design and fabrication methodology for the CCCC and PCCC moulds are presented. The main advantage gained from using epoxy was the ability to produce profiled conformal cooling channels (PCCC) fabricated with RT techniques. The fabricated mould cavities and core are to be used in the injection moulding experiments to investigate the relative cooling performance of circular channels and profiled channels.

Profiled channel is a novel concept which could be beneficial for reducing the cooling times in the injection moulding process and for the overall reduction in the process cycle time resulting in cost saving for the process.

The benefits of Rapid Tooling with injection moulds fabricated with aluminium filled epoxy can be overshadowed due to the low thermal conductivity of epoxy material. In the current work, another innovative idea was studied which was to embed a metal insert in the epoxy mould to enhance the thermal conductivity of the mould. The part moulded was exactly the same in all the moulds. Another variation of the metal insert idea which is a conformal insert with straight cooling channels was also studied and fabricated in the current research.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the results and discussions on a novel technique of fabricating cooling channels and two novel techniques for cooling time reduction in plastic injection moulds made with Aluminum Filled Epoxy material. In the current research, the thermal performance of the cooling channel geometry is analyzed with ANSYS and experimented in an injection mould fabricated with epoxy. Another technique was also analyzed and experimented in which a conducting metal insert was embedded within the epoxy injection mould.

The chapter starts with the results on the calculation of the Shape Factor for different channel geometries followed by the transient thermal analysis for CCCC, PCCC, CCCC+Insert and PCCC+Insert moulds done by ANSYS software. After the thermal analysis results, the experimental results for the configuration of the above moulds are presented.

Thermal performance in plastic injection mould is a vital issue and has a significant effect on production cycle time, cost and part quality. For the optimization of the moulding process, it is important to reduce moulding cycle time which also has significant effect on the quality of the product.

4.2 Steady State Analysis for Channel Geometries

A temperature of 180°C was applied on the cavity side and at the wall of the cooling channel, a temperature of 30°C was applied.

After solving, the model heat flow at the cavity was obtained.

Temperature applied at cavity = T_1 = 180°C

Temperature applied at channel = T_2 = 30°C

Heat Flow = q = 5.78 Watts

The shape factor for this channel was calculated as follows.

From equation (3.1) from chapter 3,

$$q = Sk(T_1 - T_2) \tag{3.1}$$

Or $$S = \frac{q}{k(T_1 - T_2)}$$

For the steady state analysis, the thermal conductivity of epoxy, 0.7 W/mK was used. However, the input temperatures and thermal conductivity are only for the purpose of calculation and the Shape Factor is not affected by this choice.

After solving the Shape Factor 'S' for the circular channel geometry was found to be

$$S = \frac{q}{k(T_1 - T_2)}$$

S = 0.055 m

= 55 mm

Steady state analyses were performed for circular and other channel geometries. The results of the analyses are shown in Figures 4.1 to 4.5.

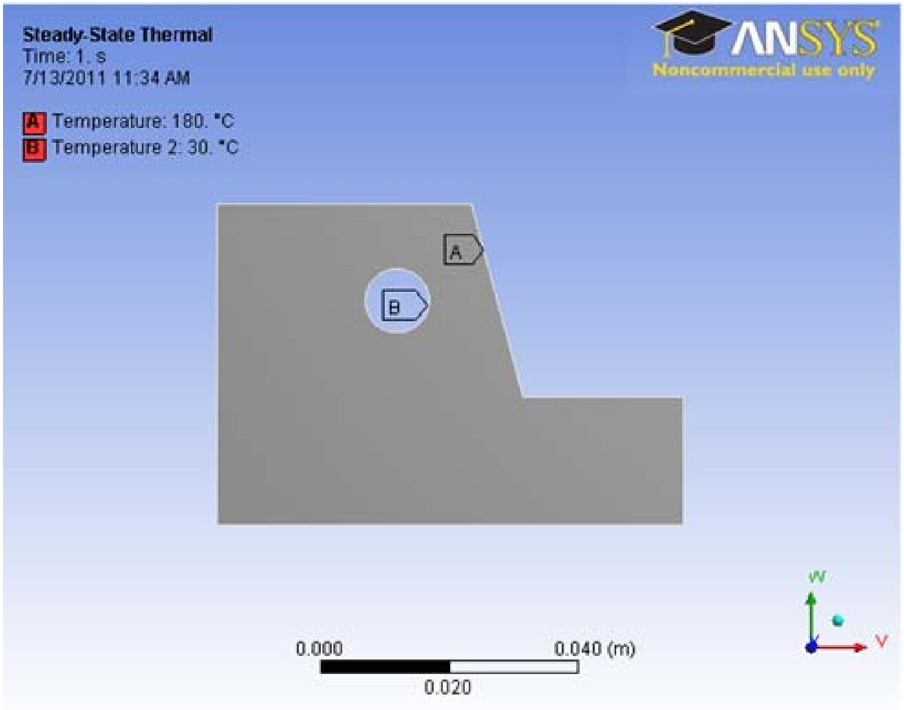


Figure 4.1 Circular Channel Geometry Analysis

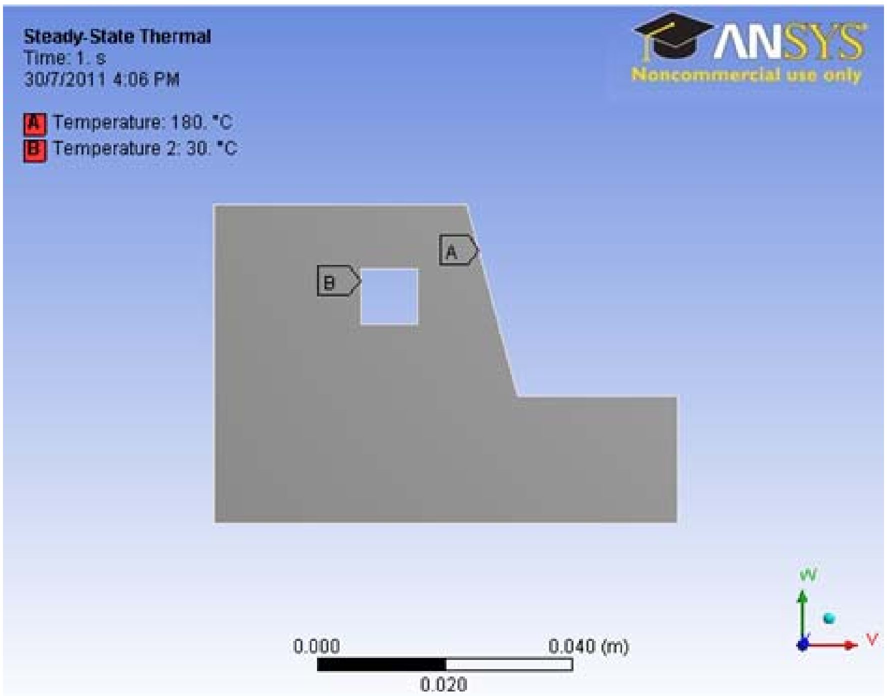


Figure 4.2 Square Channel Geometry Analysis

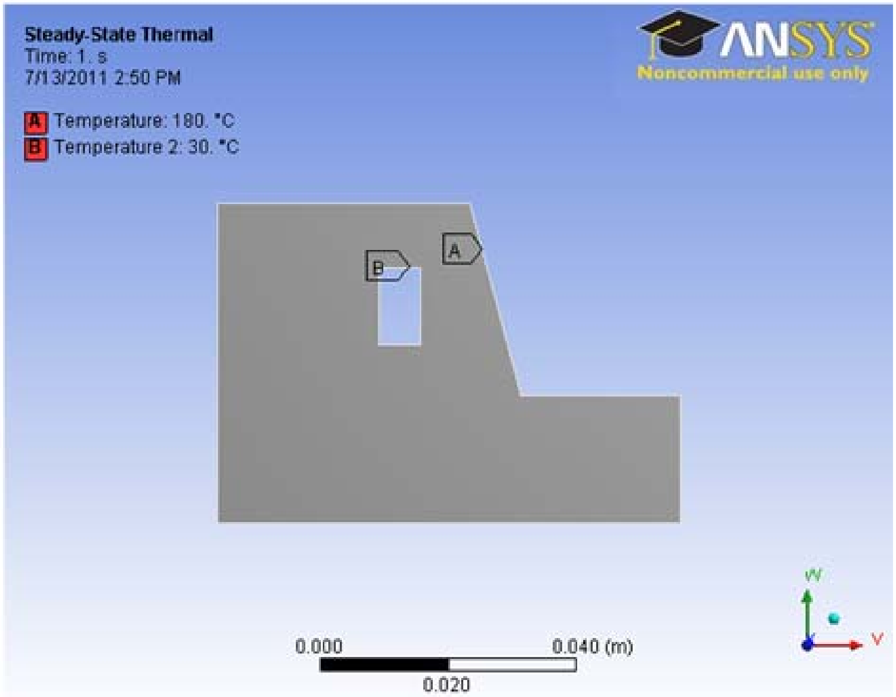


Figure 4.3 Rectangular Channel 1 Geometry Analysis

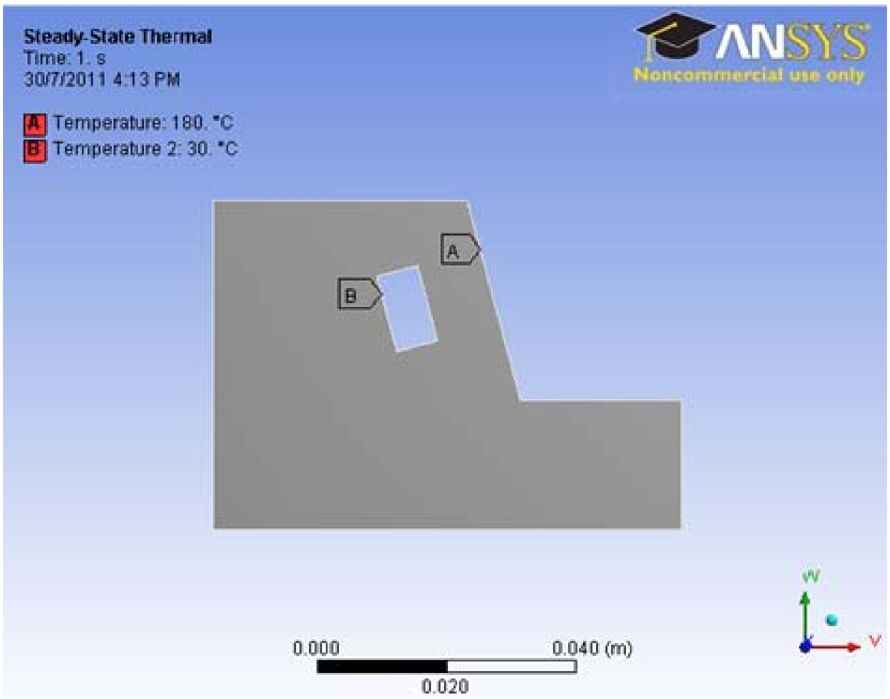


Figure 4.4 Rectangular Channel 2 Geometry Analysis

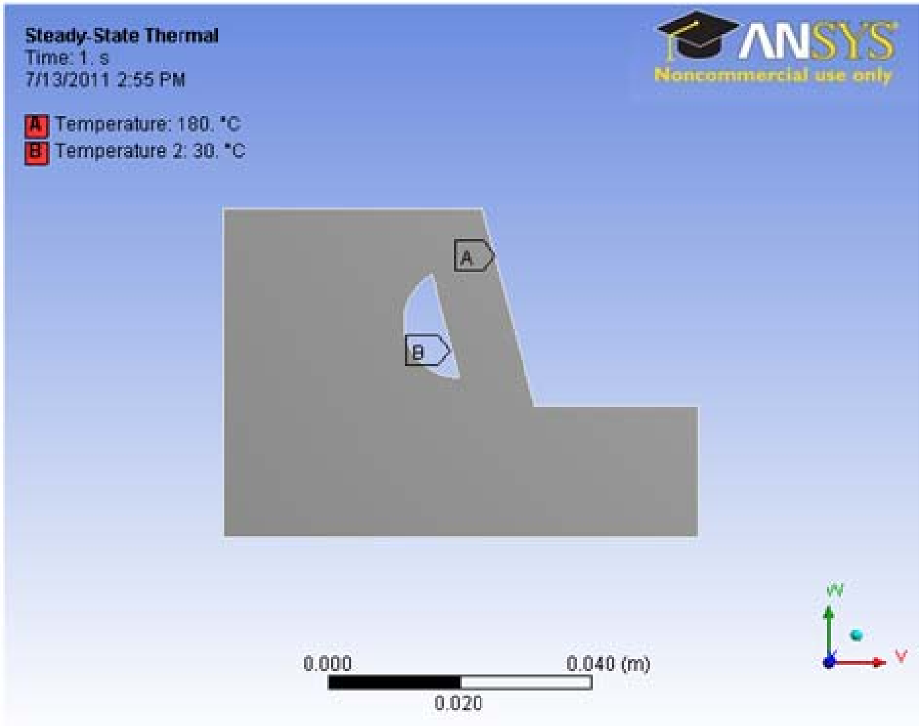


Figure 4.5 Profiled Channel Geometry Analysis

4.2.1 Shape Factor Calculation for Channel Geometries

The data obtained after solving the analysis models and the shape factor for various channel geometries is given in Table 4.1

Table 4.1 Shape Factor for Different Channel Geometries

Channel Type	Heat Flow (Watts)	Temperature T_1 °C	Temperature T_2 °C	Shape Factor (mm)
Circular	5.78	180	30	55
Square	5.71	180	30	54.3
Rectangular 1	6.05	180	30	57.6
Rectangular 2	6.76	180	30	64.3
Profiled	7.31	180	30	69.6

From the calculation of the shape factor, it is observed that the Profiled Channel geometry has the maximum shape factor value as compared to other geometries. This means that this channel geometry will have the best thermal performance for the given cavity shape. This is because the cooling channel has the highest degree of conformance with the cavity shape.

4.2.2 Discussion of Results for Shape Factor

The shape factor yields estimates of the relative cooling performance of the cooling channel geometries. From these estimates, decisions regarding the selection of suitable geometries for further analysis could be made. The boundary temperatures and heat transfer coefficients are typical values that exist in practice. The shape factor is merely a measure of the inverse of diffusion depth in the conduction regime. The larger the shape factor, the smaller is the mean distance for heat flow. This in turn translates as higher heat flow rate and shorter time of cooling of the part.

Though the actual cooling time and behavior of the mould is through a 3-dimensional transient analysis, the steady state solution of a 2-D problem yields the essential information that can be helpful in the initial estimates.

4.3 Transient Thermal Analysis for the Moulds

The initial condition of mould temperature for the analysis was set as 31^{o}C. Metal filled Epoxy material used for the analysis was created in FEA software with the following parameters supplied with the material information data for the epoxy.

Density	1650 kg/m^3
Thermal Conductivity	0.7 W/mK
Specific Heat [52]	1300 J/kg^{o}C

For a coolant velocity of 0.85m/s, the convection coefficient for the circular was calculated in section 3.7.3.1 for the circular channel as 4799 W/m^{2o}C at a water temperature of 30^{o}C.

For the profiled channel, the convection coefficient was 5005 W/m^{2o}C, considering the appropriate hydraulic diameter of the profiled channel.

4.3.1 Thermal Transient Analysis of CCCC mould

The conditions for transient analysis are given below

Analysis Settings

No of steps	2
Duration of time Step 1	30 seconds
Duration of time Step 2	1200 seconds

For determining heat dissipation, the temperature probe was used on the cavity surface. The transient analysis temperature curve for CCCC mould is shown in Figure 4.6 and temperature distribution at the end of the simulation is shown in Figure 4.7.

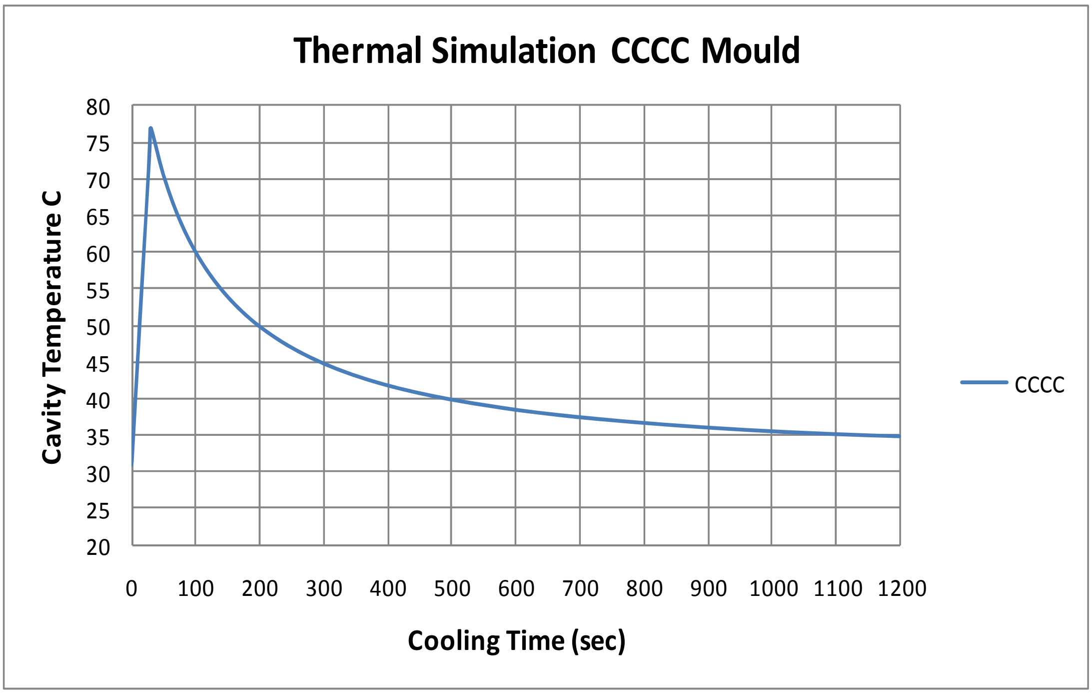


Figure 4.6 Transient Thermal Temperature Graph CCCC Mould

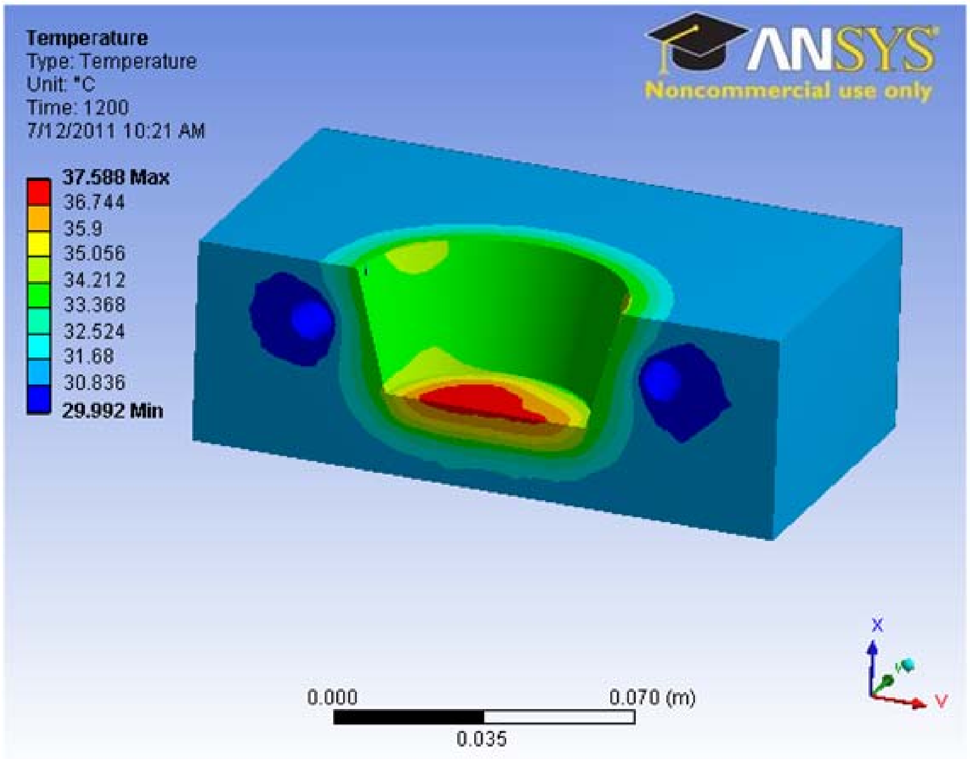


Figure 4.7 Temperature distribution at the end of the Simulation for the CCCC Mould

4.3.2 Transient Analysis of PCCC mould

The conditions for transient analysis are given below

<u>Analysis Settings</u>

No of steps	2
Duration of time Step 1	30 seconds
Duration of time Step 2	1200 seconds

For determining the heat dissipation, the temperature probe was used on the cavity surface. The transient analysis temperature versus time curve for PCCC mould is shown in Figure 4.8 and temperature distribution at the end of the simulation is shown in Figure 4.9.

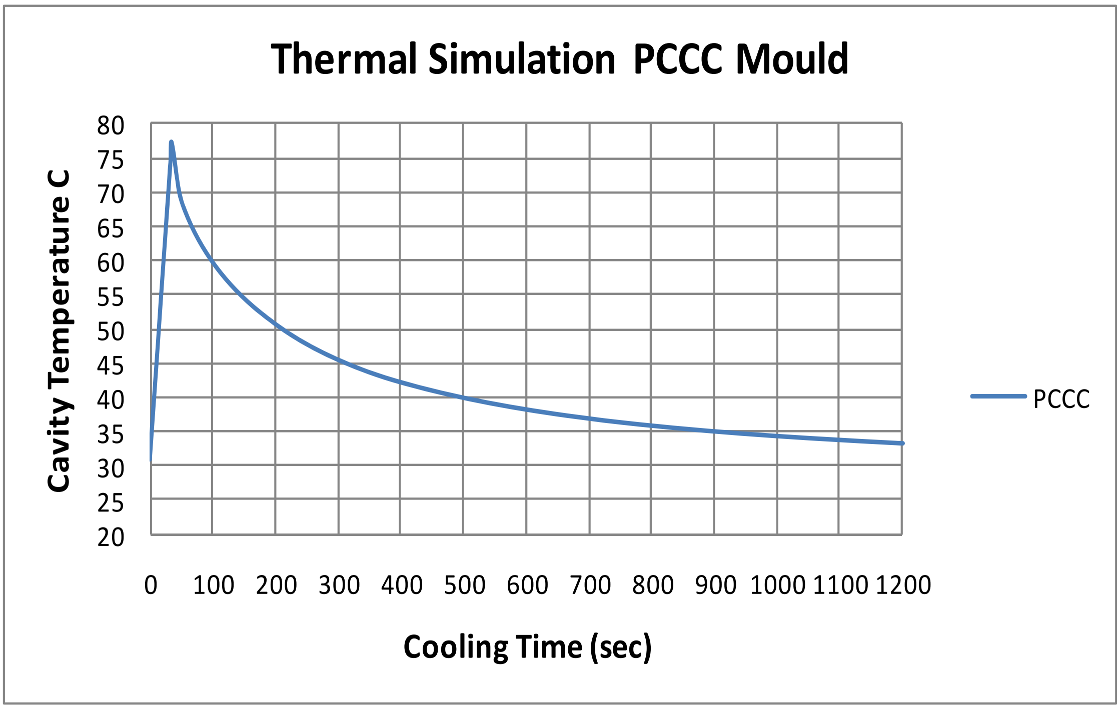


Figure 4.8 Transient Thermal Temperature Graph-PCCC Mould

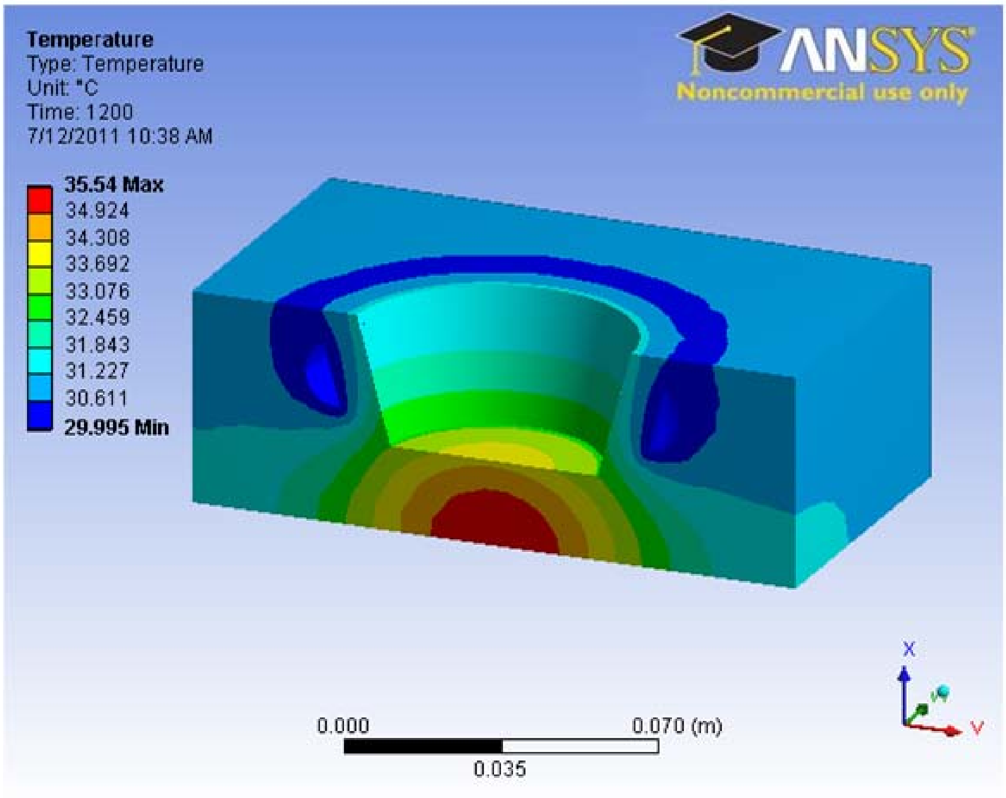


Figure 4.9 Temperature distribution at the end of Simulation-PCCC Mould

4.3.3 Transient Analysis CCCC+Insert mould

The conditions for transient analysis are given below

<u>Analysis Settings</u>

No of steps	2
Duration of time Step 1	30 seconds
Duration of time Step 2	1200 seconds

For determining heat dissipation, the temperature probe was used on the cavity surface for CCCC+Insert mould. The transient analysis curve for CCCC+Insert mould is shown in Figure 4.10 and temperature distribution at the end of the simulation is shown in Figure 4.11.

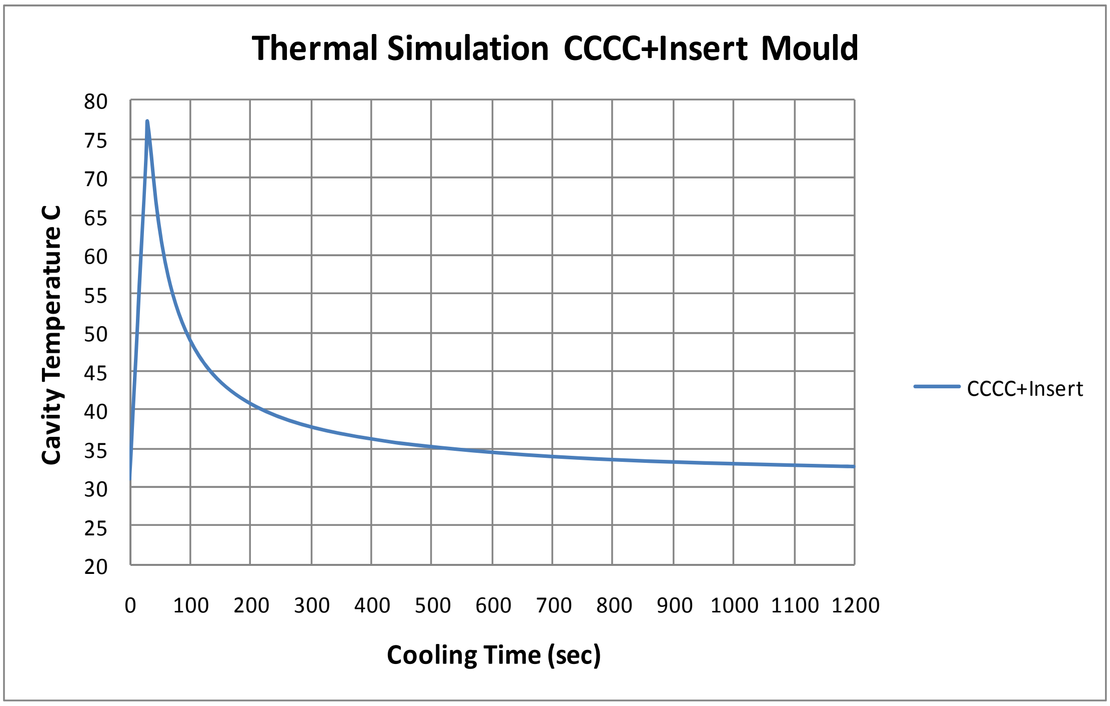


Figure 4.10 Transient Thermal Temperature Graph for CCCC+Insert Mould

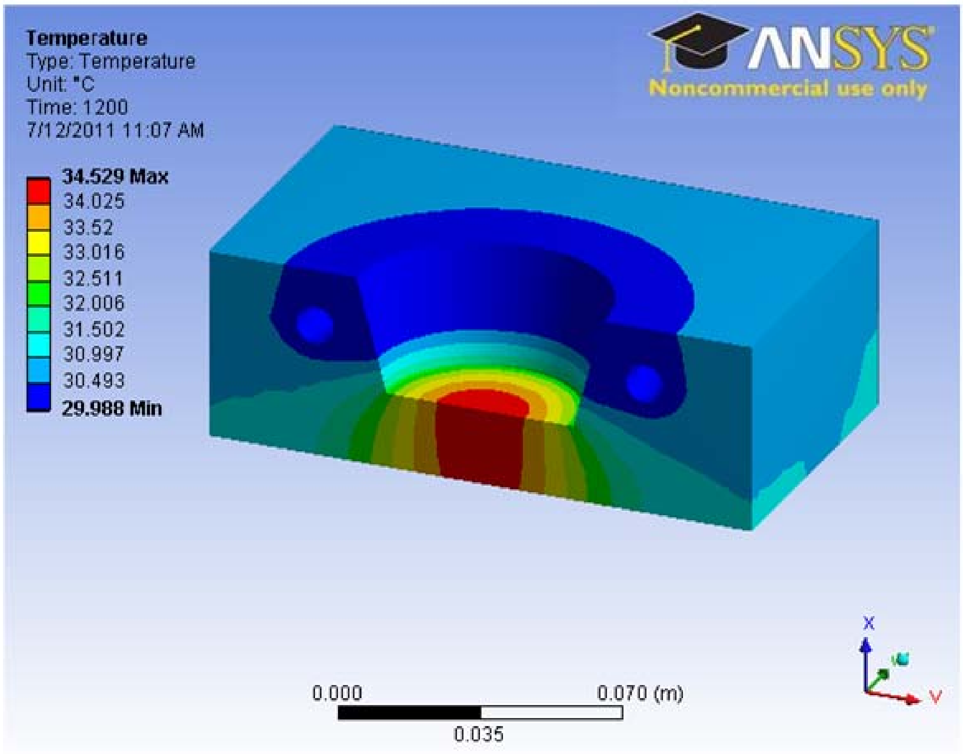


Figure 4.11 Temperature distribution at the end of Simulation-CCCC+Insert Mould

4.3.4 Transient Analysis PCCC+Insert mould

The conditions for transient analysis are given below

Analysis Settings

No of steps	2
Duration of time Step 1	30 seconds
Duration of time Step 2	1200 seconds

For determining heat dissipation, the temperature probe was used on the cavity surface of PCCC+Insert mould. The transient analysis curve for PCCC+Insert mould is shown in Figure 4.12 and temperature distribution at the end of the simulation is shown in Figure 4.13.

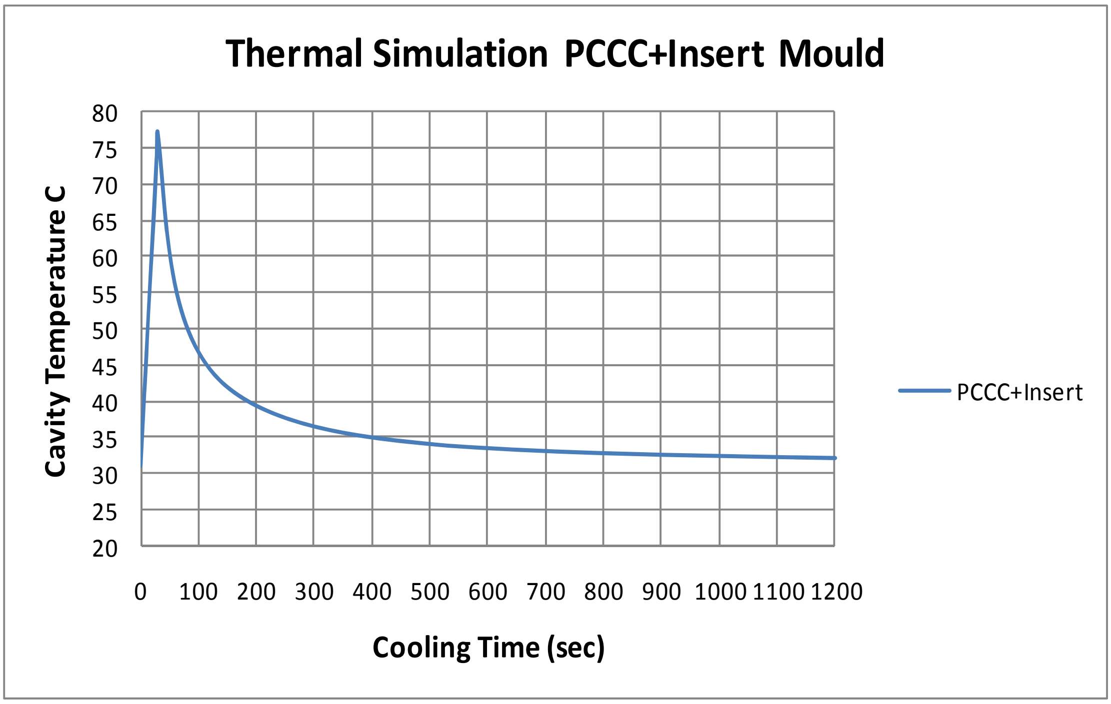


Figure 4.12 Transient Thermal Temperature Graph for PCCC+Insert Mould

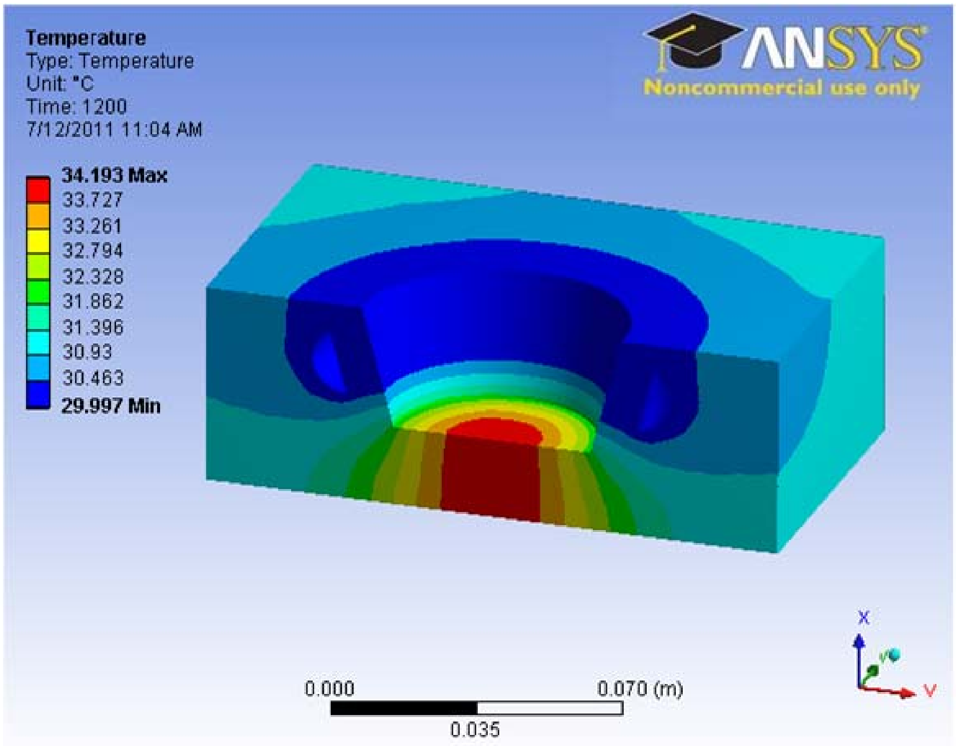


Figure 4.13 Temperature distribution at the end of Simulation-PCCC+Insert Mould

4.3.5 Discussion of Simulation Results

Transient Thermal simulations were done for all four mould configurations. The cooling time observed for each mould to reach the ejection temperature of 35^{o}C is determined as following.

CCCC Mould	1080 sec
PCCC Mould	900 sec
CCCC+Insert Mould	510 sec
PCCC+Insert Mould	390 sec

The simulation results showed that the PCCC mould has better cooling characteristics as compared to CCCC mould and hence better heat dissipation. The same pattern followed in the moulds with inserts and the PCCC+Insert mould has better cooling time than CCCC+Insert mould. Also both moulds with inserts had far better heat dissipation than moulds without inserts. This effect is due to the high conductive aluminum insert embedded within the mould. With the aid of thermal simulations, the better thermal performance for moulds was observed and it builds the confidence for the experimental part for the research.

4.4 Injection Moulding Experiments

4.4.1 Temperature History for Injection Moulding Experiments

The temperature data from the 5 thermocouples were recorded with the data logger. Several runs of injection moulding were done and the temperature data was recorded.

After the moulding runs, the stored digital data file was converted with the aid of data logger software into a file format which can be opened by the Microsoft Excel spread sheet software for data analysis.

4.4.2 Injection Moulding Experimental Data for CCCC Mould

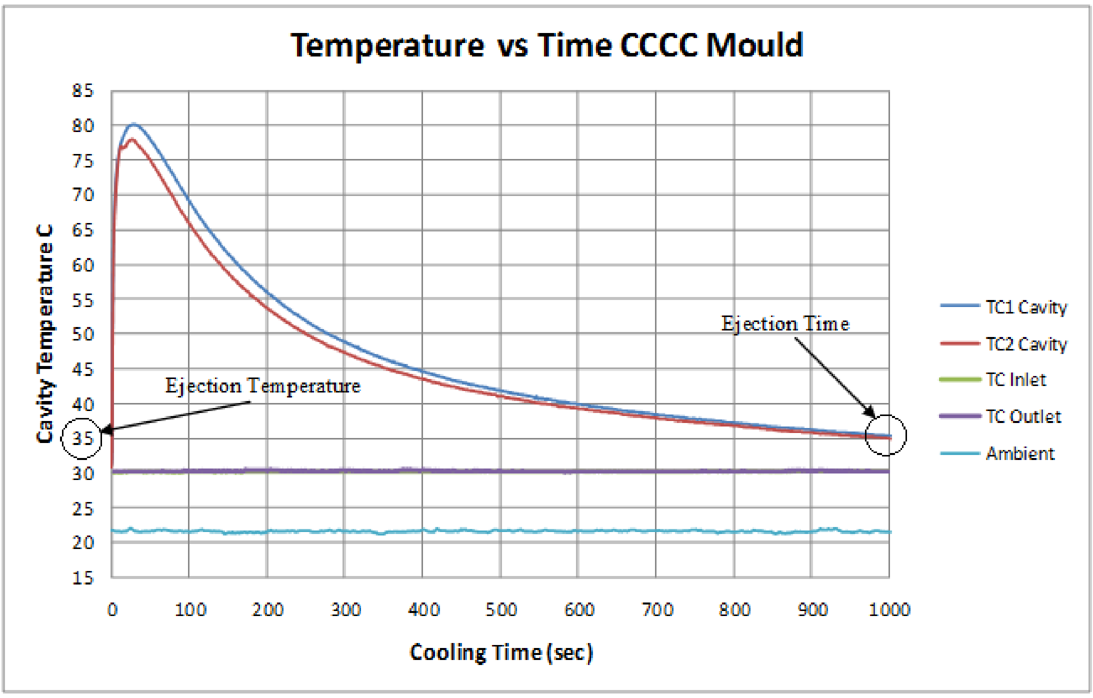


Figure 4.14 Temperature versus Time Graph for CCCC Mould Experimental Run 1

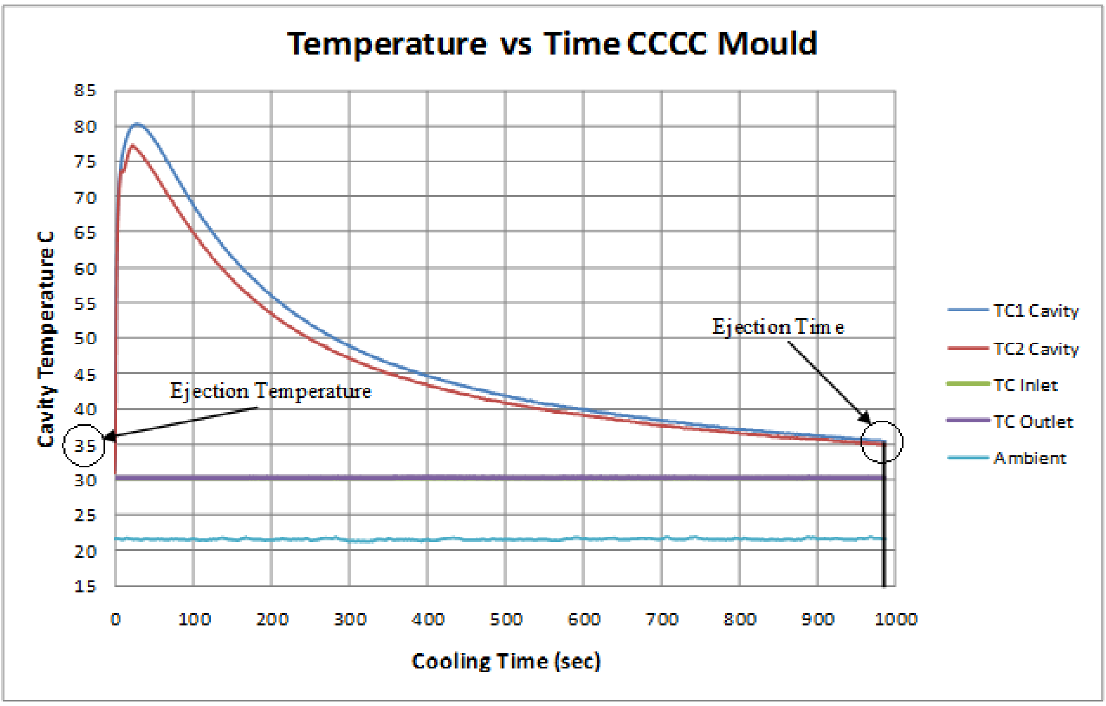


Figure 4.15 Temperature versus Time Graph for CCCC Mould Experimental Run 2

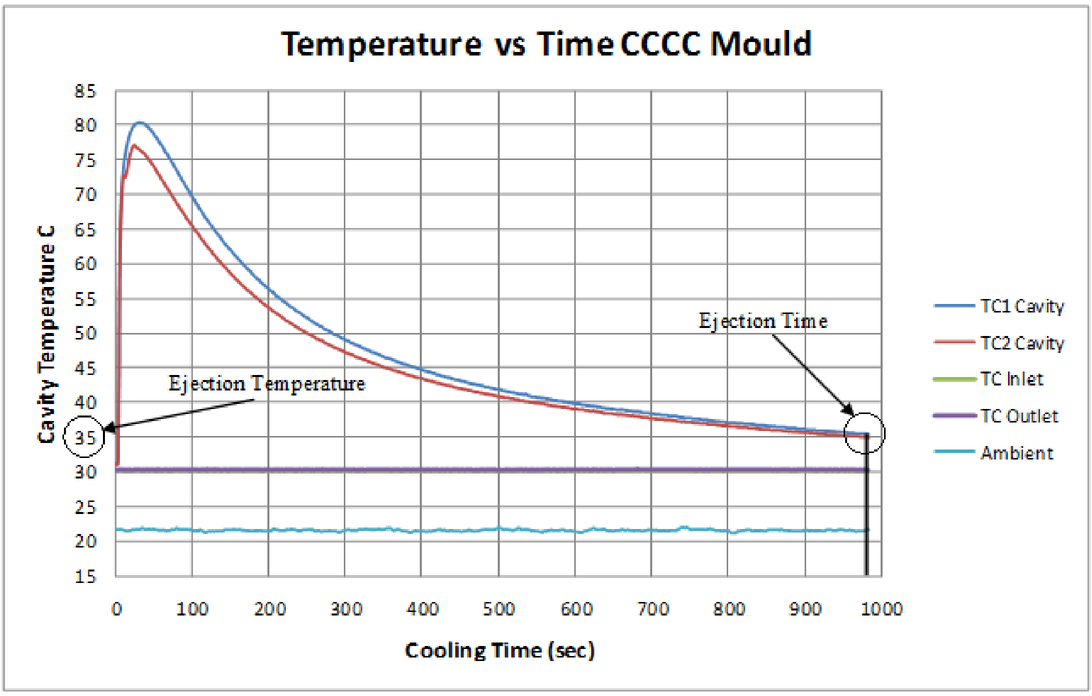


Figure 4.16 Temperature versus Time Graph for CCCC Mould Experimental Run 3

4.4.3 Injection Moulding Experimental Data for PCCC Mould

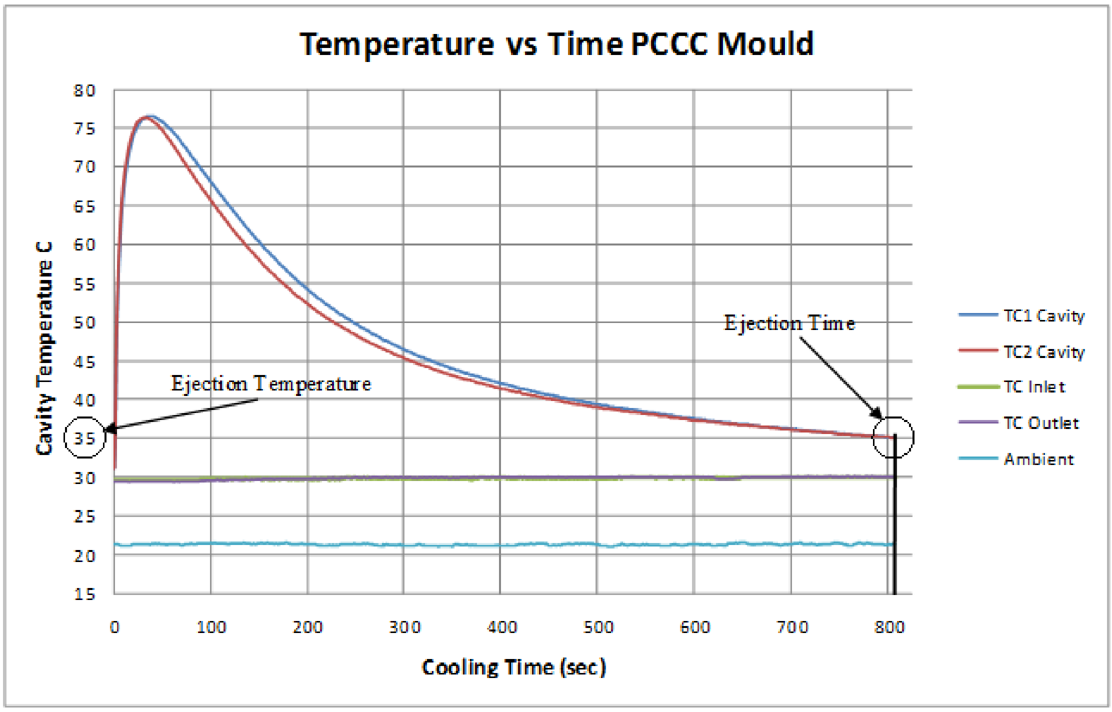


Figure 4.17 Temperature versus Time Graph for PCCC Mould Experimental Run

Temperature measurements were recorded for both CCCC and PCCC moulds for the experimental injection moulding runs. Figures 4.14, 4.15 and 4.16 are the temperature versus time graphs for CCCC mould. The three CCCC results are practically identical and demonstrate the reproducibility of the results for experimental runs. The slight difference in the two temperature peaks in CCCC moulds is due to minor uncertainties in thermocouple positioning and placement. Lines for water temperature at inlet and outlet shown in the graphs are overlapping because the difference in their temperatures is very small and the two lines are viewable separately at enlarged view of the temperature trace.

4.4.4 Temperature Data Comparison for CCCC & PCCC Moulds

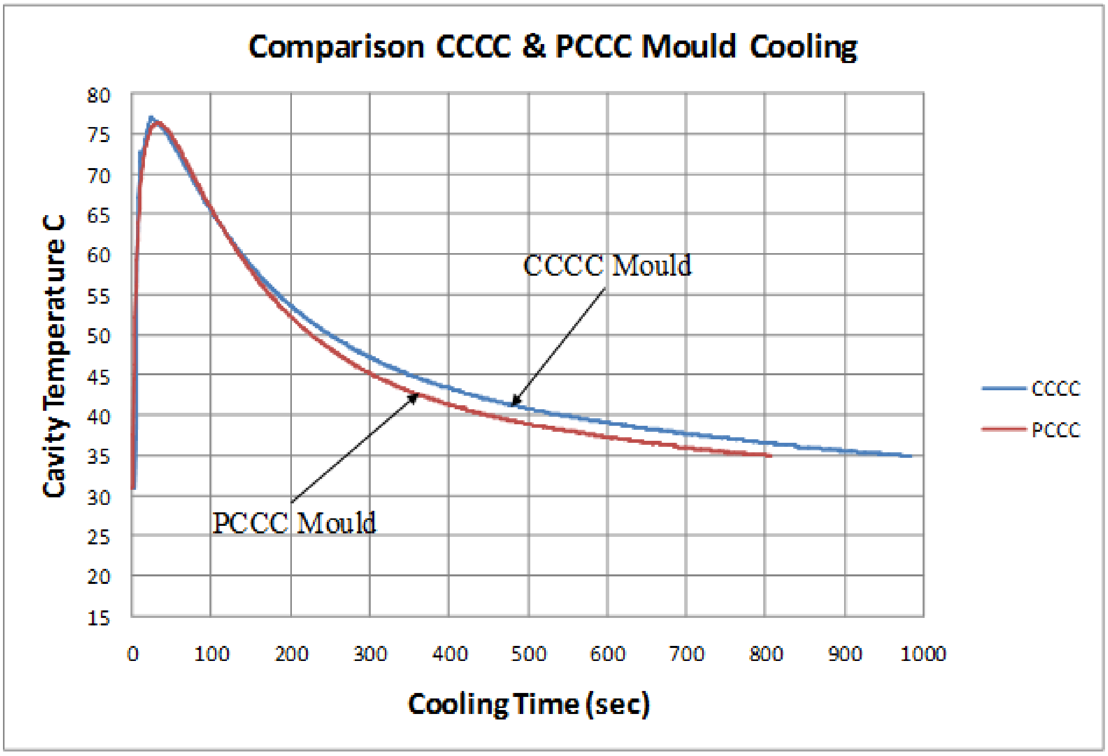


Figure 4.18 Cooling Time Comparison CCCC and PCCC Moulds

4.4.5 Discussion of Results for CCCC and PCCC Moulds

Analysis of the temperature data has shown that the PCCC mould dissipates heat faster than CCCC mould. Figure 4.17 is the temperature versus time graph for PCCC mould and Figure 4.18 is the cooling time comparison between CCCC and PCCC moulds. The percentage time reduction in PCCC moulds as compared to CCCC moulds are shown in Table 4.2 corresponding to the graph in Figure 4.19.

Table 4.2: Percentage Reduction in Cooling Times, CCCC and PCCC mould

	CCCC Mould	PCCC Mould	Percentage Reduction
Time (sec) for reaching Ejection Temperature of 35°C	983	807	17.90%

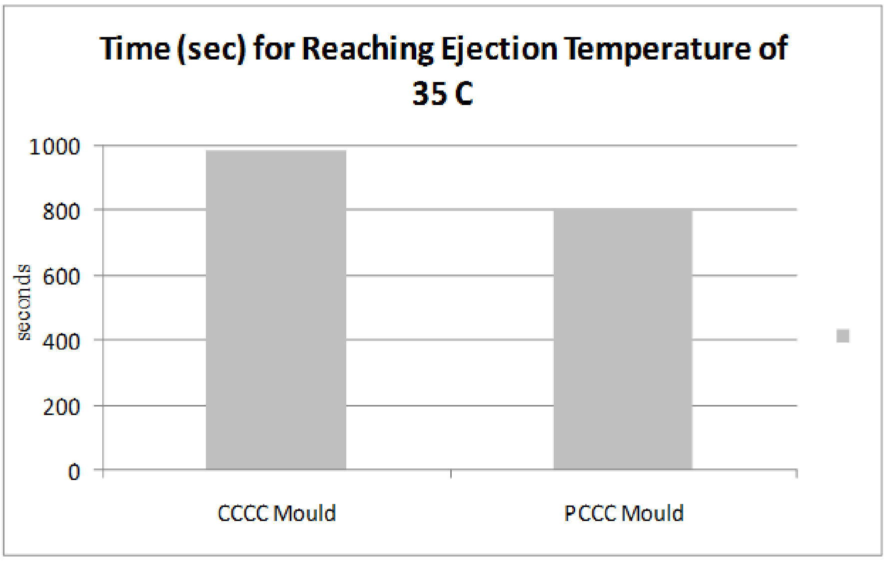


Figure 4.19 Time to Reach Ejection Temperature for CCCC and PCCC Moulds

Better cooling characteristics of the profiled cooling channel that can be seen from the above results can be explained based on two favorable mechanisms that complement each other.

The first aspect is based on the hydraulic diameter of the cooling channel. The circular cooling channel has the smallest periphery for a given area of flow cross section. Any deviation from the circular section, such as an elliptical or rectangular shape, increases the periphery for a given cross sectional area. The modified flow passage helps to reduce the distance through which heat diffusion occurs in the coolant. This fact is emphasized by the concept of hydraulic diameter, which is proportional to the cross sectional area divided by the passage perimeter.

Thus for given cross sectional area and a larger perimeter, the hydraulic diameter is smaller, implying that the distance for heat to diffuse into the coolant is also shorter. The profiled channel cross-section shown in Figure 4.20 is reproduced here from chapter 3.

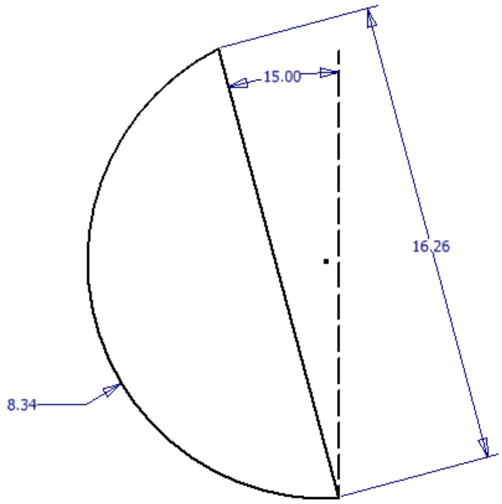


Figure 4.20 Cross-section of Profiled Channel

Hydraulic Diameter $= D_H = \frac{4 \text{ x Cross-sectional area}}{\text{Wetted perimeter}}$

Reynold's number, Re = $\frac{\rho VD}{\mu}$

Heat transfer coefficient h = $\frac{k}{D}$ 0.027 $[(Re)^{0.8}\ x\ (Pr)^{0.33}]$

Results of calculations given below in Table 4.3 indicate in quantitative terms the effect of profiling the channel.

Table 4.3 Results of Heat Transfer Calculation

No.	Detail	Circular Passage	Profiled Passage
1	Area	78.5 mm^2	78.5 mm^2
2	Hydraulic Diameter, mm	10	8.1
3	Reynold's Number	10,604	8,590
4	Nusselt's Number	78.73	66.52
5	Heat Transfer Coefficient W/m^2 K	4799	5005

The second aspect of heat transfer enhancement is hereby addressed.

Referring to Figures 4.21a and 4.21b shown below, it is observed that in the epoxy mould and external to the coolant flow passage, the path for heat conduction is favorably modified by a suitably chosen cooling channel geometry.

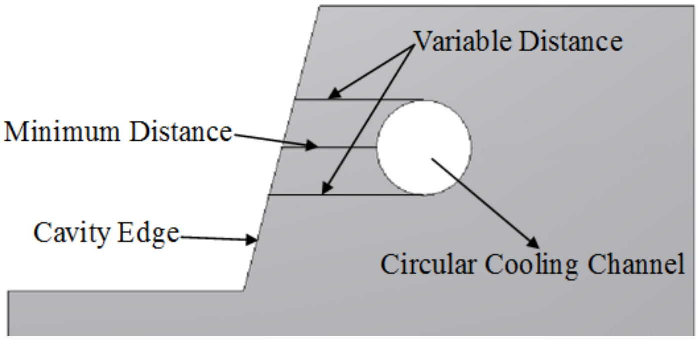


Figure 4.21a Heat diffusion distance for CCCC

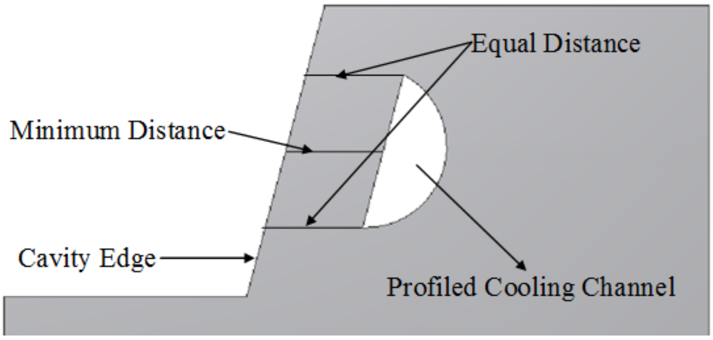


Figure 4.21b Heat diffusion distance for PCCC

When the cooling channel is profiled so as to follow the contour of the cavity, the heat conduction depth through the mould is more uniform and shorter as observed in these figures. Thus, with improved convection in the coolant and better conduction in the mould, a dual advantage is derived for heat discharge from the cast part to the heat sink. The faster heat flow inevitably leads to more rapid cooling of the part as seen in Table 4.2 above, resulting in the reduction of cooling time from 983 seconds for CCCC to 807 seconds for PCCC.

The PCCC mould has about 18 percent less cooling time as compared to CCCC mould. This indicates that the mould with profiled channel dissipates heat faster as compared to circular channel.

Profiled channel is a novel concept which will be beneficial for reducing the cooling times in the injection moulding process and for the overall reduction in the process cycle time.

4.5 Experiments of Moulds with Embedded Aluminum Inserts

4.5.1 Temperature Measurement

The temperature data from the 5 thermocouples were recorded and logged with the data logger. The data logger was programmed as per the injection moulding parameters. Several runs of injection moulding were done and temperature data was recorded. Data was analyzed for the temperature measurement for the CCCC+Insert mould and PCCC+Insert mould.

4.5.2 Injection Moulding Experiment CCCC+Insert Mould

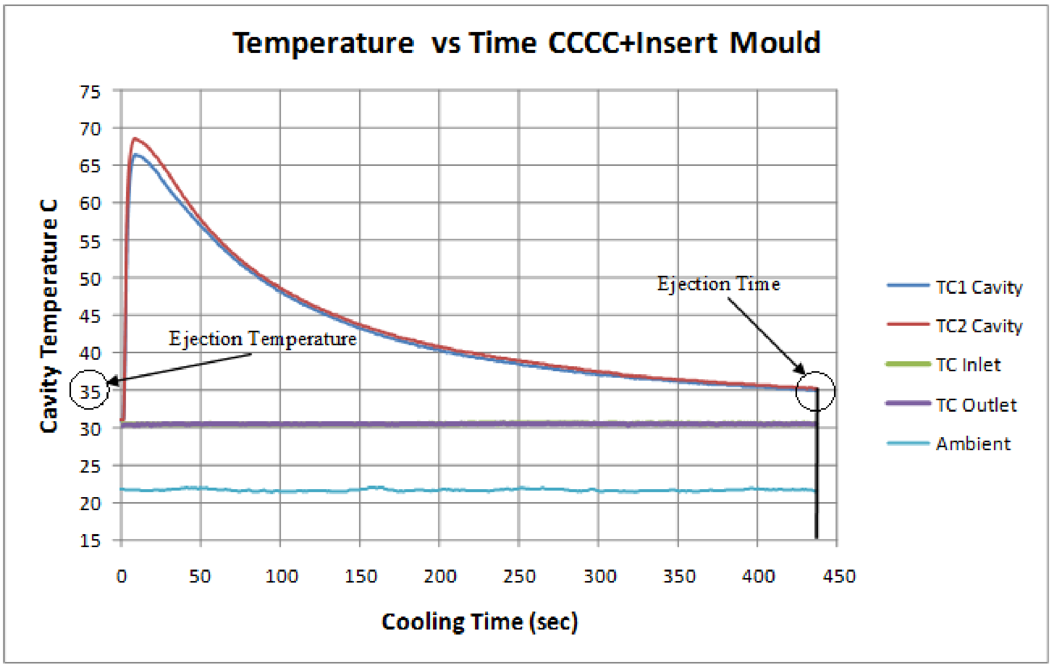


Figure 4.22 Temperature versus Time Graph for CCCC+Insert Mould Experimental Run 1

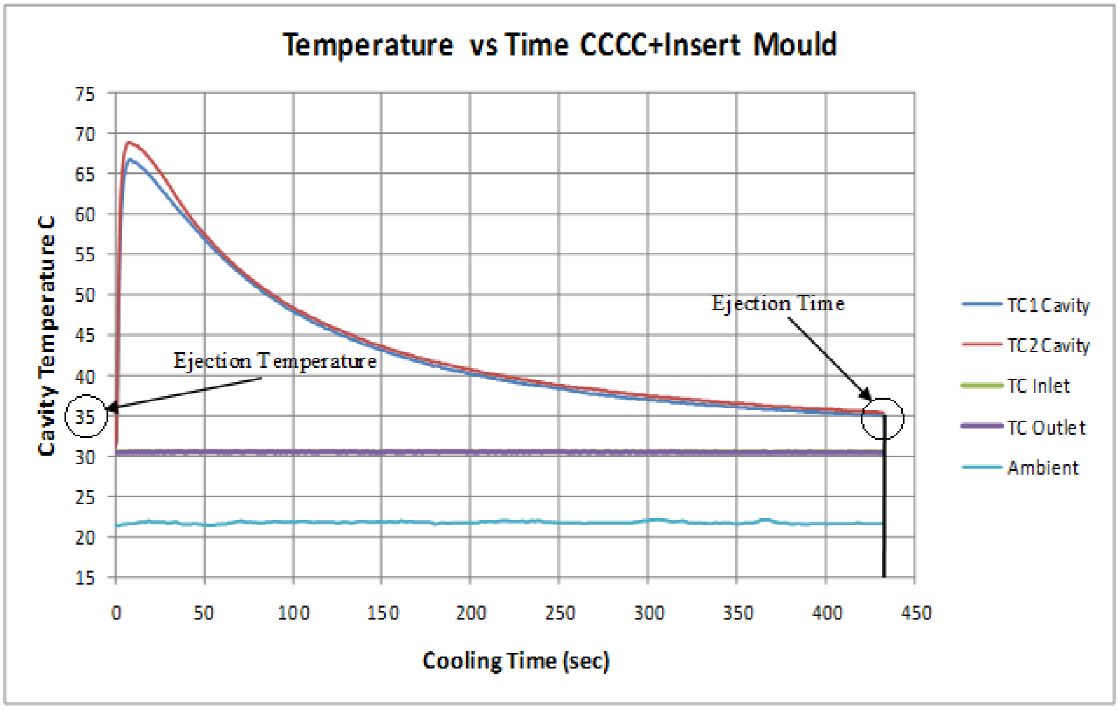


Figure 4.23 Temperature versus Time Graph for CCCC+Insert Mould Experimental Run 2

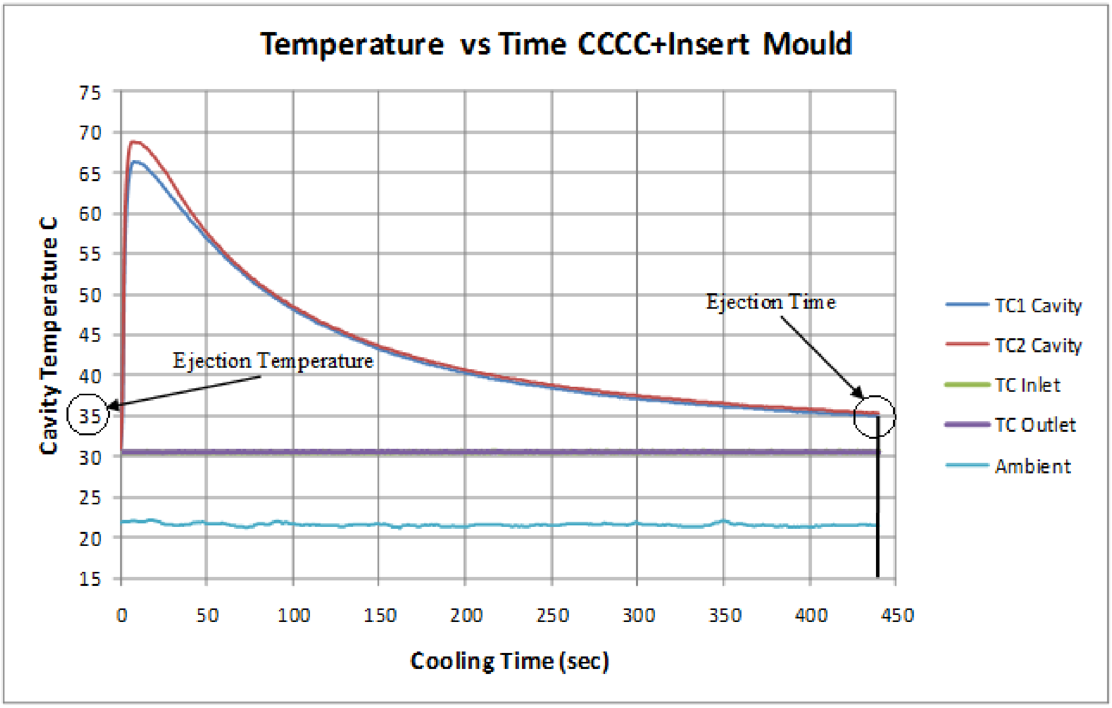


Figure 4.24 Temperature versus Time Graph for CCCC+Insert Mould Experimental Run 3

4.5.3 Injection Moulding Experiment PCCC+Insert Mould

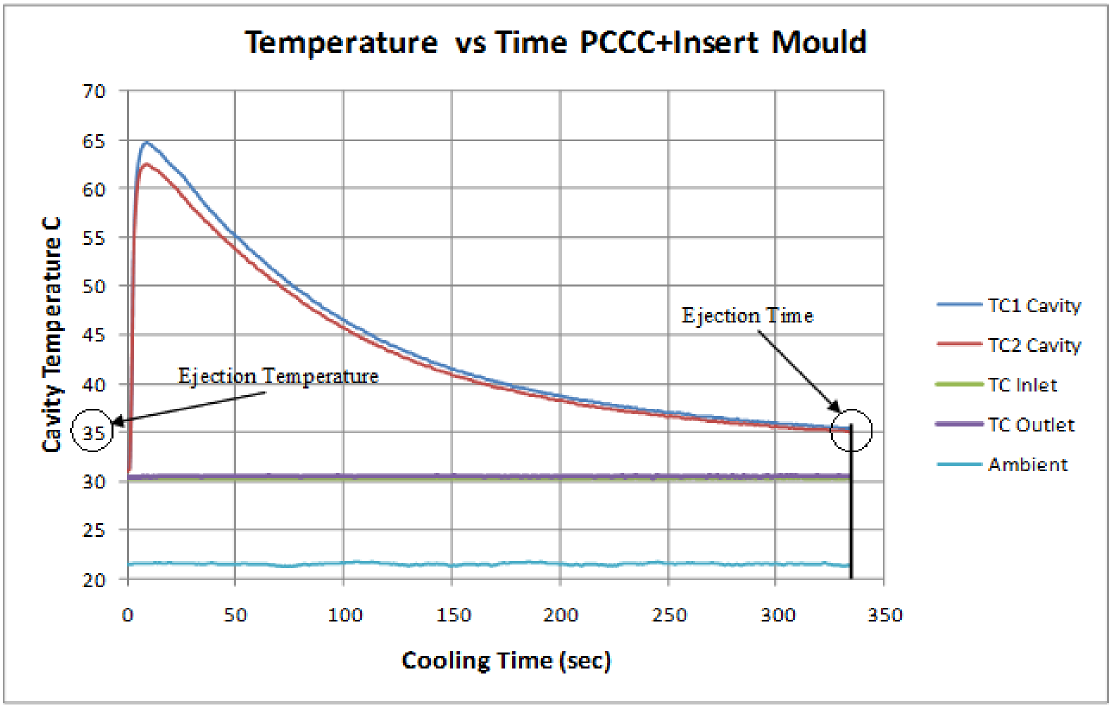


Figure 4.25 Temperature versus Time Graph for PCCC+Insert Mould

4.5.4 Data Comparison for CCCC & PCCC Insert Moulds

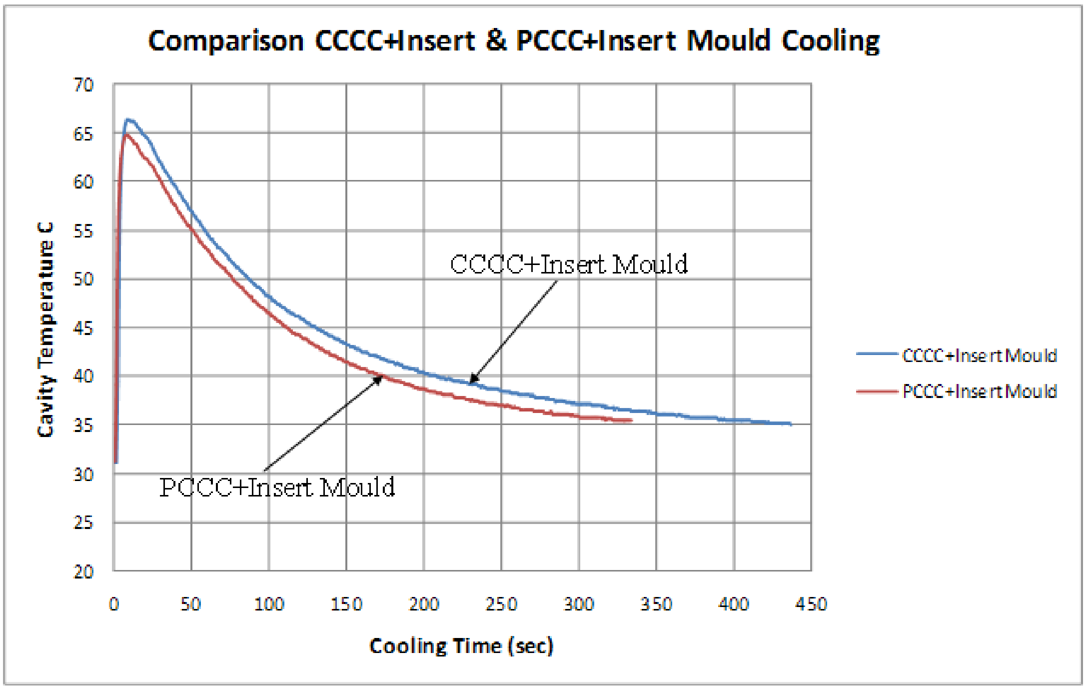


Figure 4.26 Cooling Time Comparison CCCC+Insert and PCCC+Insert Moulds

Temperature measurements were recorded for CCCC and PCCC moulds with conducting metal inserts for the experimental injection moulding runs. Figures 4.22, 4.23 and 4.24 are the temperature versus time graphs for CCCC+Insert moulds. The results are identical and demonstrate the reproducibility of the moulds. The small difference in the temperature peaks in the two cavity thermocouples is due to minor uncertainties in the positioning and placement of the two thermocouples. Lines for water temperature at inlet and outlet shown in the graphs are overlapping because the difference in their temperatures is very small and the two lines are viewable separately at enlarged view of the temperature trace. Figure 4.25 shows the cooling time for PCCC+Insert mould and Figure 4.26 shows the cooling time comparison between CCCC+Insert and PCCC+Insert moulds.

4.5.5 Injection Moulding Experiment Conformal Insert Mould

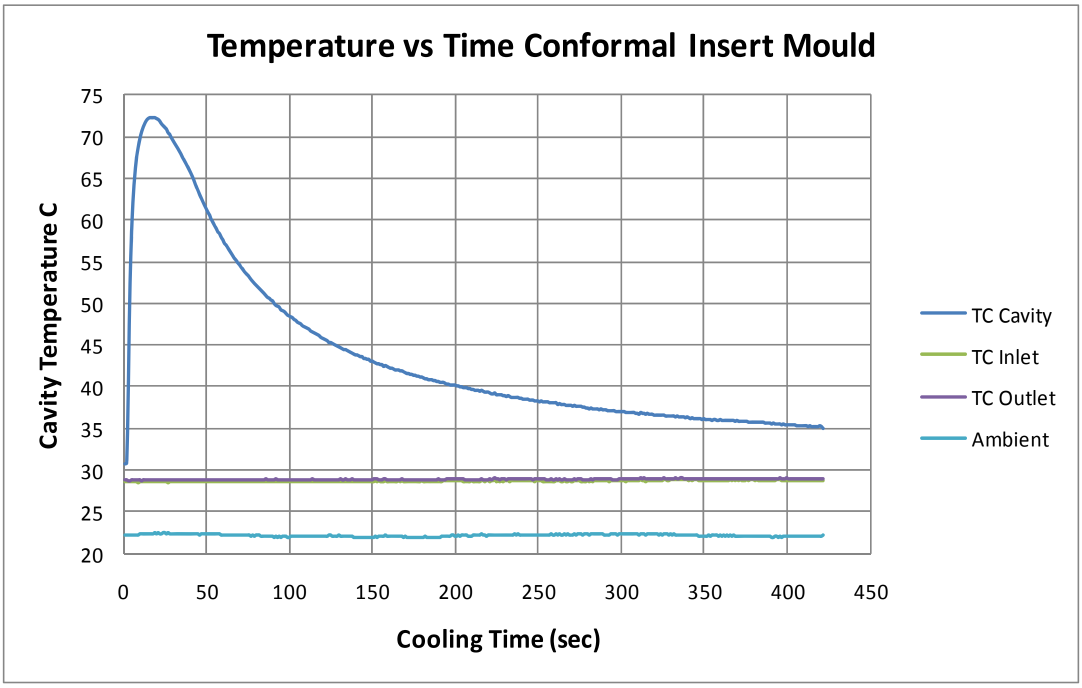


Figure 4.27 Temperature versus Time Graph for Conformal Insert Mould

4.5.6 Discussion of Results for CCCC and PCCC Embedded Inserts Moulds and Conformal Insert Mould

Due to the low thermal conductivity of epoxy, the shorter cooling time with PCCC in Rapid Tooling injection moulds fabricated with epoxy can lead to only trivial benefits. Dispersion of aluminum powder in epoxy effects only small changes in its thermal conductivity. As thermal conduction is the governing heat flow mechanism in the cooling of epoxy moulds, another concept was considered, namely, the placement of conducting inserts in the mould. This was the reason that a second technique was studied and experimented during the research to assess the thermal performance of the same moulds, with CCCC and PCCC, having metal inserts embedded within the mould cavities.

It was observed from the earlier results that the epoxy mould with PCCC dissipates heat faster than the mould with CCCC. But still the cooling time for epoxy moulds is still substantially long due to the poor thermal conductivity of epoxy. The benefits of Rapid Tooling with injection moulds fabricated with aluminum filled epoxy can be overshadowed due to the low thermal conductivity of epoxy material. The experimental analysis showed that the cooling time in the insert moulds is far less than CCCC, PCCC moulds without conducting inserts. The part moulded was exactly the same in all the moulds.

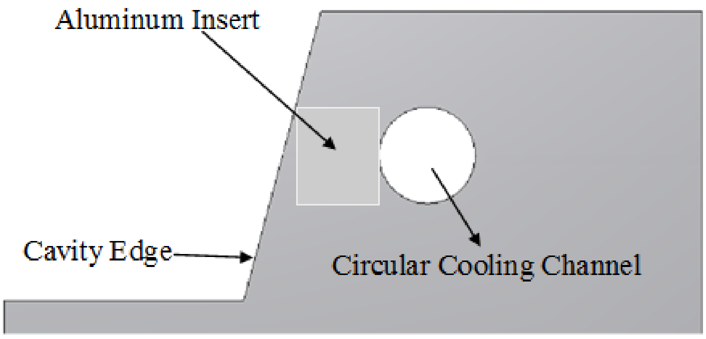


Figure 4.28a CCCC Mould with Insert

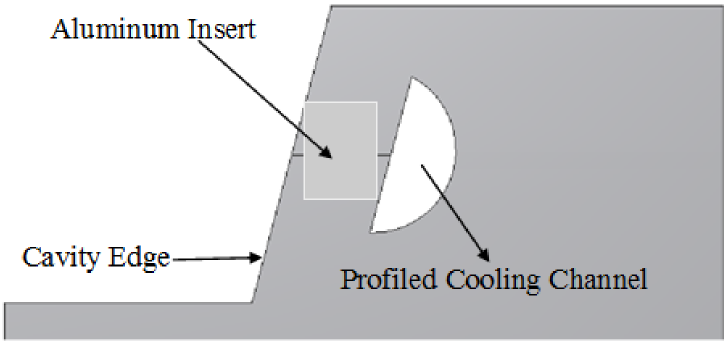


Figure 4.28b PCCC Mould with Insert

Hence an idea to embed thermally conducting metal insert within the mould between the cavity and the cooling channel was envisaged to enhance the effective thermal conductivity of the mould. This technique is expected to further increase the effective thermal conductivity of the epoxy mould, leading to further reduction in cooling time for the part. The technique was implemented in both CCCC and PCCC moulds. The (CCCC+Insert) and (PCCC+Insert) moulds are shown in Figures 4.28a and 4.28b reproduced here from chapter 3.

Analysis of the temperatures data has shown that PCCC+Insert mould is dissipating heat faster than CCCC+Insert mould. This phenomenon was also seen in the moulds without inserts. The percentage time reduction in PCCC+Insert moulds as compared to CCCC+Insert moulds are shown in Table 4.4 corresponding to the graph in Figure 4.29.

Table 4.4: Percentage Reduction in Cooling Times, CCCC+Insert and PCCC+Insert moulds

	CCCC+Insert Mould	PCCC+Insert Mould	Percentage Reduction
Time (sec) for reaching Ejection Temperature of 35^{o}C	437	334	23.56%

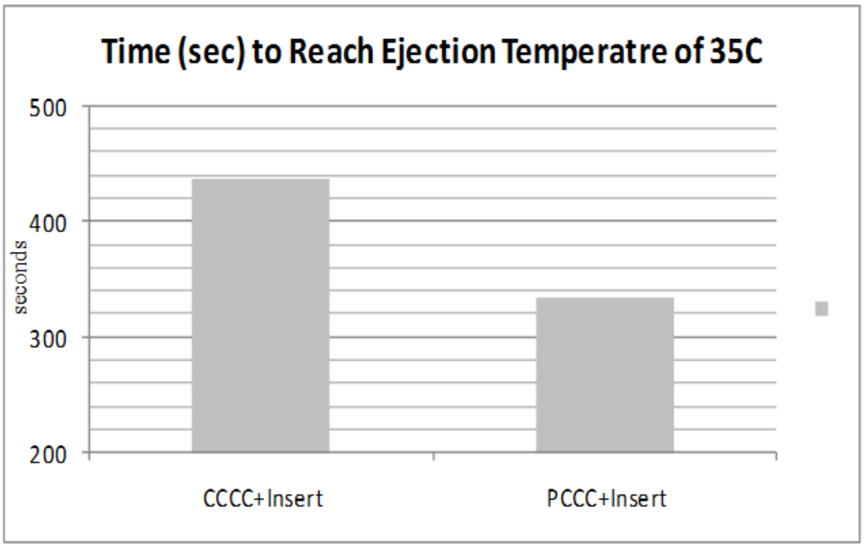


Figure 4.29 Time to Reach Ejection Temperature for CCCC+Insert and PCCC+Insert Moulds

Another variation in the conducting insert concept using a simple straight cooling channel with an insert conformal with the part on one side as well as with the cooling channel on the other was also studied. It is reproduced here in Figure 4.30 from chapter 3.

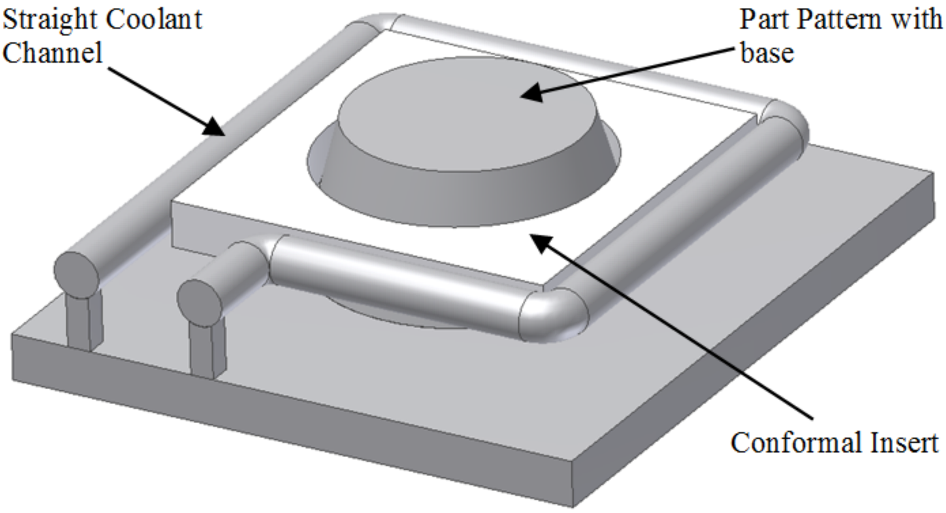


Figure 4.30 Conformal Insert with Straight channels

The cooling time to reach ejection temperature of 35°C for moulds having CCCC+insert and conformal insert was almost same. The temperature trace for conformal insert mould is shown in Figure 4.27. The injection time for the conformal insert mould was 422 seconds as shown in Figure 4.27 as compared to the time of 437 seconds for the CCCC+Insert mould. This shows that by using the conformal insert, the time for cooling to ejection temperature is approximately the same as with circular conformal channel and inserts mould. Both of these mould configurations have circular cross sectional channels. The difference is that the CCCC+insert has conformal channel while the other mould has straight channels but with conformal insert which conforms to the cavity from inside and conforms to the cooling channel from outside as seen in Figure 4.30. The cooling times for these moulds is given in Table 4.7 with a corresponding graph in Figure 4.31. The part produced with injection moulding experiments is shown in Figure 4.32.

Table 4.5 Ejection Time for Moulds with Inserts

Mould Type	CCCC+Insert	Conformal Insert
Time (sec) to Reach Ejection Temperature of 35°C	437	422

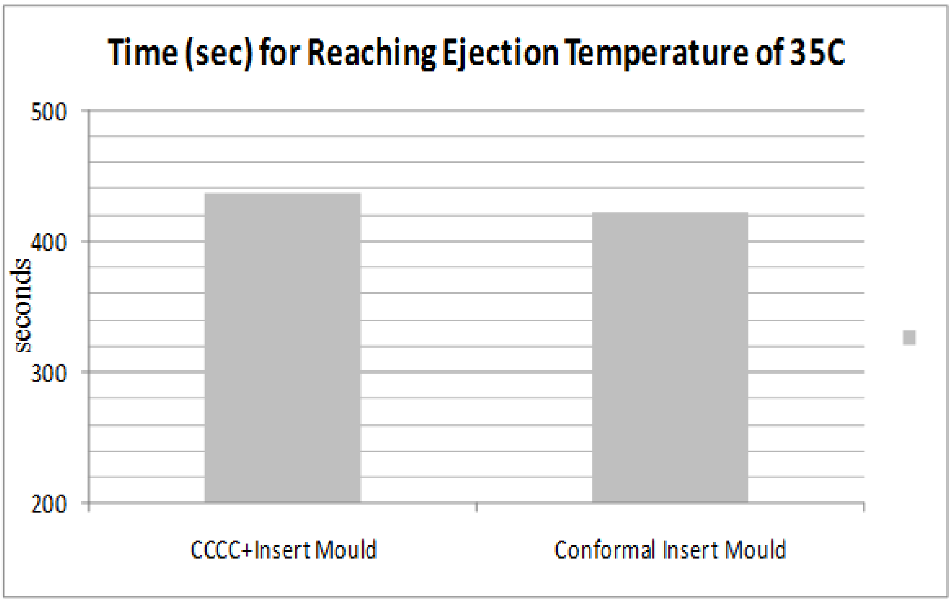


Figure 4.31 Time to Reach Ejection Temperature for CCCC+Insert and Conformal Insert moulds

Figure 4.32 Part produced with Injection Moulding

4.6 Comparative Results of Simulations and Experiments

Numerical simulation is an essential tool to predict the thermal behavior and performance for injection mould tools and it can yield overall savings in process cycle time and costs. Hence a full three-dimensional transient numerical simulation was carried out. The results of the simulations could be used for modifications in future mould designs and cooling channel configurations without a need for verification through further experiments. Using this numerical model, simulation was run for all mould configurations and their results were examined.

The comparative plots between experiments and analysis are presented below for discussion. Figure 4.33 is the comparative plot of CCCC mould, Figure 4.34 is the comparative plot for PCCC mould, Figure 4.35 is the comparative plot for CCCC+Insert mould and Figure 4.36 is the comparative plot for PCCC+Insert mould.

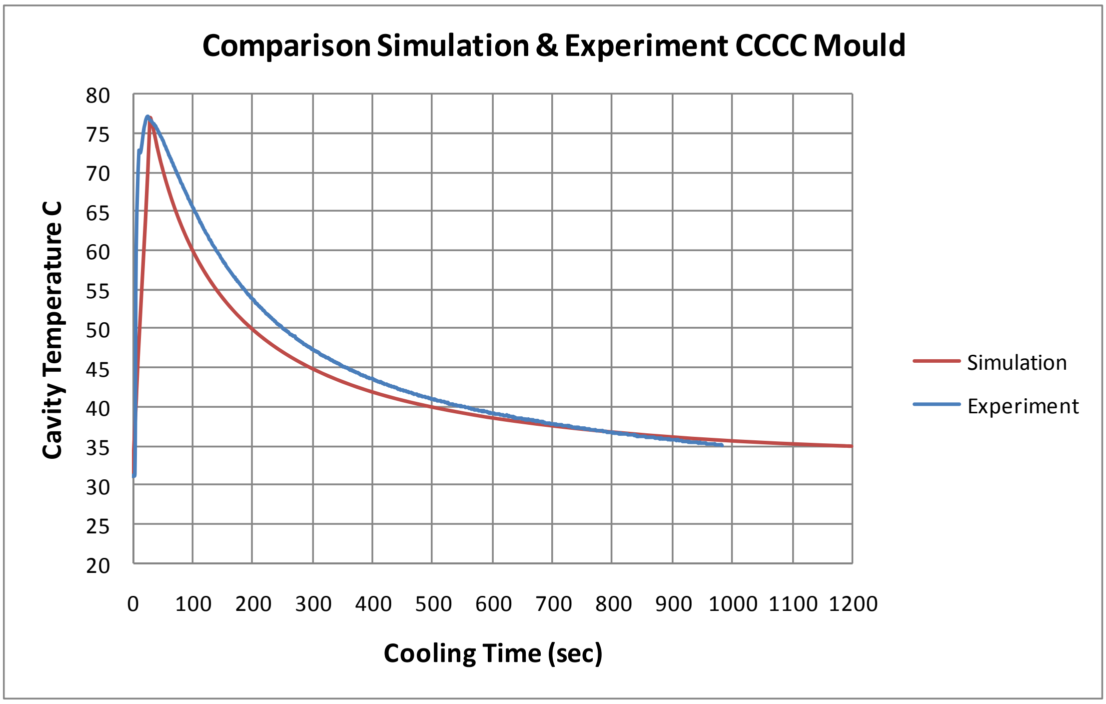


Figure 4.33 Comparative plots Simulation and Experiment CCCC Mould

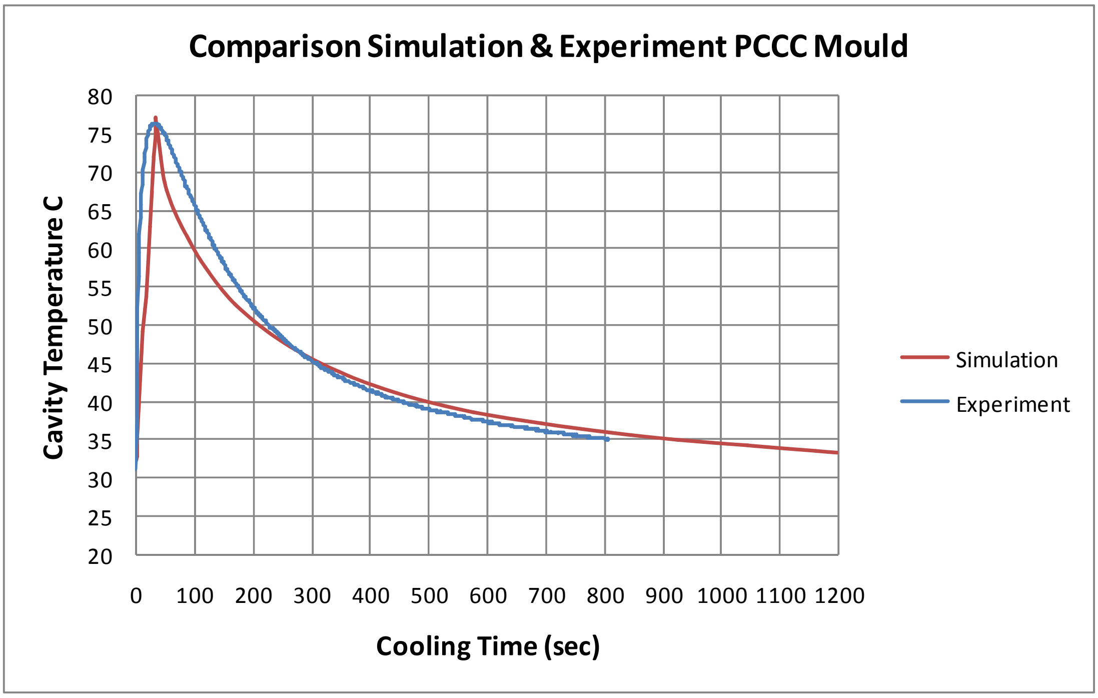


Figure 4.34 Comparative plots Simulation and Experiment PCCC Mould

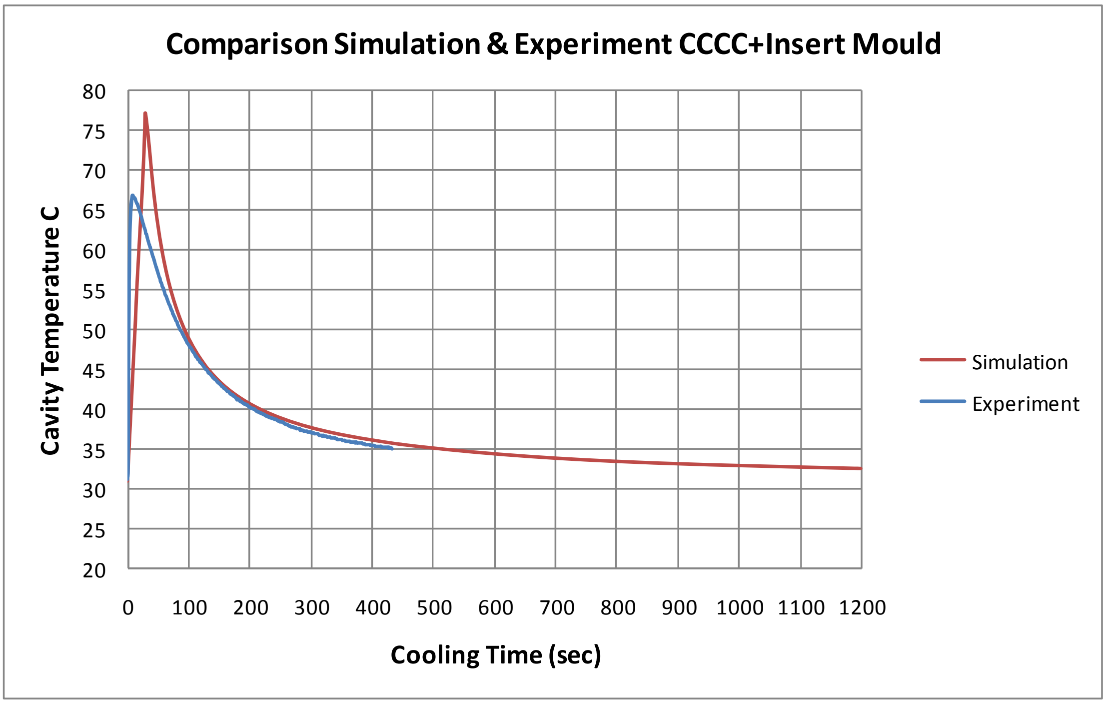


Figure 4.35 Comparative plots Simulation and Experiment CCCC+Insert Mould

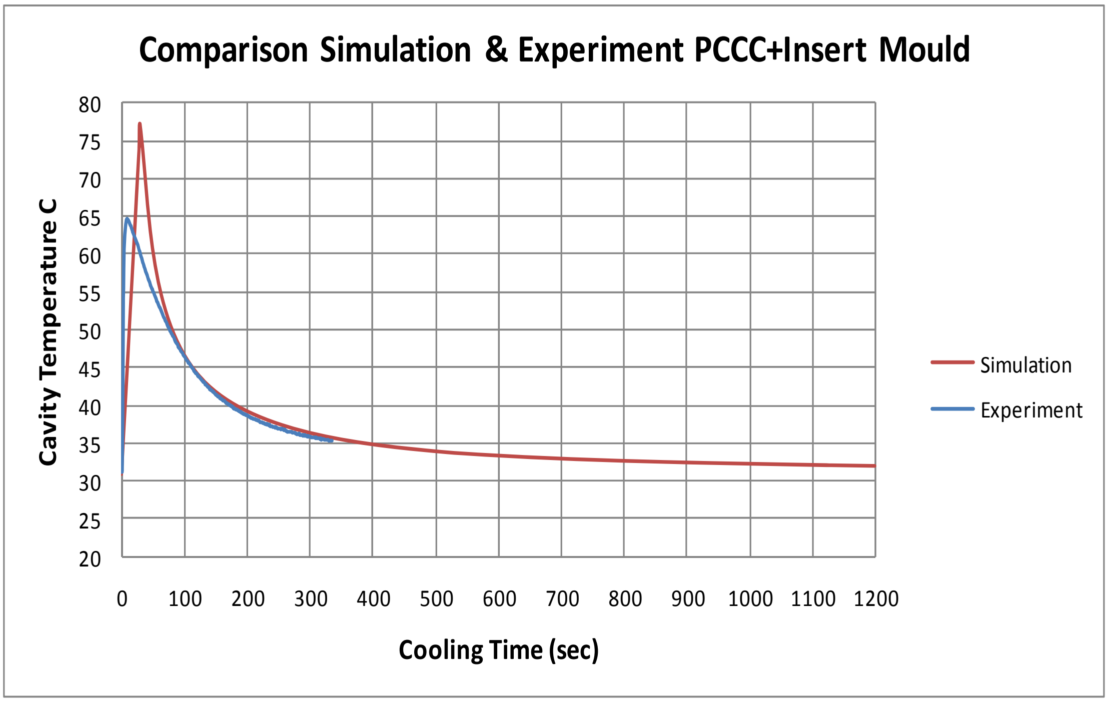


Figure 4.36 Comparative plots Simulation and Experiment PCCC+Insert Mould

4.6.1 Discussions of Results

The above plots show that there is good agreement between experiments and simulation. From the comparison of simulated and experimental results shown above, it was observed that the variation of cooling time to reach the ejection temperature of 35°C is quite small. Hence this simulation model can be recommended for the thermal performance analysis of injection moulds as it would satisfactorily predict the cooling characteristics.

From Figure 4.33 to Figure 4.36 following cooling times were observed for experimental and simulation curves and given in Table 4.5.

Table 4.6: Cooling Time Comparison, Experiment and Simulation

Mould Type	Experimental Time (seconds)	Simulation Time (seconds)	Percentage difference
CCCC	983	1080	9
PCCC	807	900	10
CCCC+Insert	437	510	15
PCCC+Insert	334	390	14

The cooling time data analysis showed that the cooling times difference between the experiments and simulation is within the limits. Also there is good matching of cooling time curves for the experimental and simulation curves as seen in Figure 4.33 to Figure 4.36. The spike of the simulation trace seen in Figures 4.35 and 4.36 are due to the imposed temperature of 77^{o}C which was obtained by the trial experiment. This imposed temperature was applied as the thermal loading condition in the thermal analysis of all configurations of the moulds. The peak appears on account of the imposed temperature of polymer obtained from the trial experiment. The experimental trace represents the temperature at the interface of polymer and epoxy. When heat is extracted faster by the insert moulds, this interfacial temperature is lower and also it is a proof that heat dissipation is faster.

4.7 Mould Cooling Time Comparison

The time taken for the moulded part to reach the ejection temperature of 35^{o}C for the four types of moulds is indicated in Table 4.6, with a corresponding bar graph in Figure 4.37.

Table 4.7 Ejection Time for Moulds

Mould Type	CCCC	PCCC	CCCC+Insert	PCCC+Insert
Time to Reach Ejection Temperature of 35^{o}C	983	807	437	334

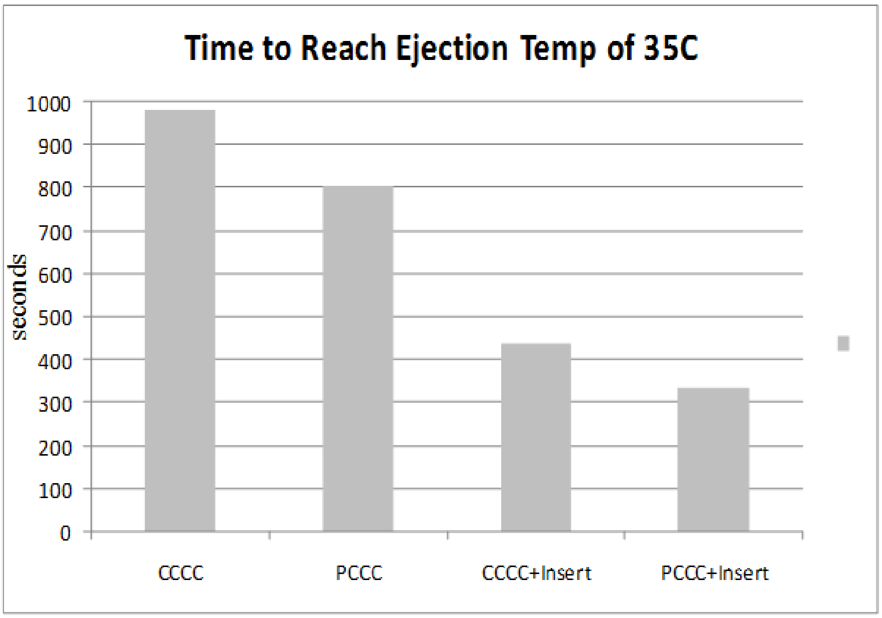


Figure 4.37 Time to Reach Ejection Temperature for Different Mould Types

The comparisons in the percentage decrease of cooling times for moulds with and without metal inserts are given in Table 4.8.

Table 4.8: Percentage reduction in Cooling Times

Mould Type		
CCCC	PCCC	Percentage Reduction in Cooling Time
983	807	17.90%

Mould Type		
CCCC	CCCC+Insert	Percentage Reduction in Cooling Time
983	437	55.50%

Mould Type		
PCCC	PCCC+Insert	Percentage Reduction in Cooling Time
807	364	58.60%

Mould Type		
CCCC+Insert	PCCC+Insert	Percentage Reduction in Cooling Time
437	334	23.50%

4.8 Critical Analysis and Comparison with other Research

The conformal cooling concept proposed by Sachs et al. [5] was used in the current research. The experimental study was on the fabrication of injection mould with conformal cooling channels (CCC) using the 3DP technique. Comparison was done for conformal channel mould with a mould having straight channels. The part design for the present study was also partially adapted from the research. The difference between the two studies is that Sachs' study was done on producing parts on an automatic injection moulding machine while the current work was done on a manual injection moulding machine. The technique used to fabricate the moulds was Three Dimensional Printing process with material as stainless steel powder. In the current research, moulds were produced using aluminum filled epoxy with patterns fabricated with Thermojet 3D printer which uses wax as the build material.

Au and Yu [44] performed a numerical analysis of a variable-radius cooling channels approach, in order to achieve more uniform cooling performance. They proposed and verified the variable radius conformal cooling channel VRCCC design and fabrication based on contemporary SFF technologies with thermal FEA and melt flow analysis. Their work indicated that heat transfer from the mould cavity surface to the cool medium circulation via VRCCC has better cooling performance and higher part quality. This approach is essentially suitable for metal moulds as this approach is more focused on the convection aspect of heat transfer. For epoxy moulds, this concept is not applicable and therefore, there is no comparable research.

An experimental study by Saifullah et al. [46] was on a square sectioned conformal channel system for injection moulds. Simulation and experimental confirmation were conducted with these new cooling channels systems. Their results provide a consistent distribution of temperature and hardness with reduced cooling time of the part. The inadequacy of the square channel approach suggested in the study is that comparisons are not made on the basis of equal flow cross-sections. In the present work, care has been taken to maintain flow area and flow velocity as identical in all cases. The shape factor analysis leads to the conclusion that the profiled channel is superior to the square channel.

4.9 Hardness Result for the Injection Moulding Part

The injection moulded part was cut in strips along the walls for the checking of hardness of parts produced with different mould configurations. A Rockwell hardness checking machine with Rockwell scale F hardness testing using 60 kg force was used for the said purpose. The ball indenter for the machine has a diameter of 1/16 inch. The standard used for hardness is ASTM E18 - 08b Standard Test Methods for Rockwell Hardness.

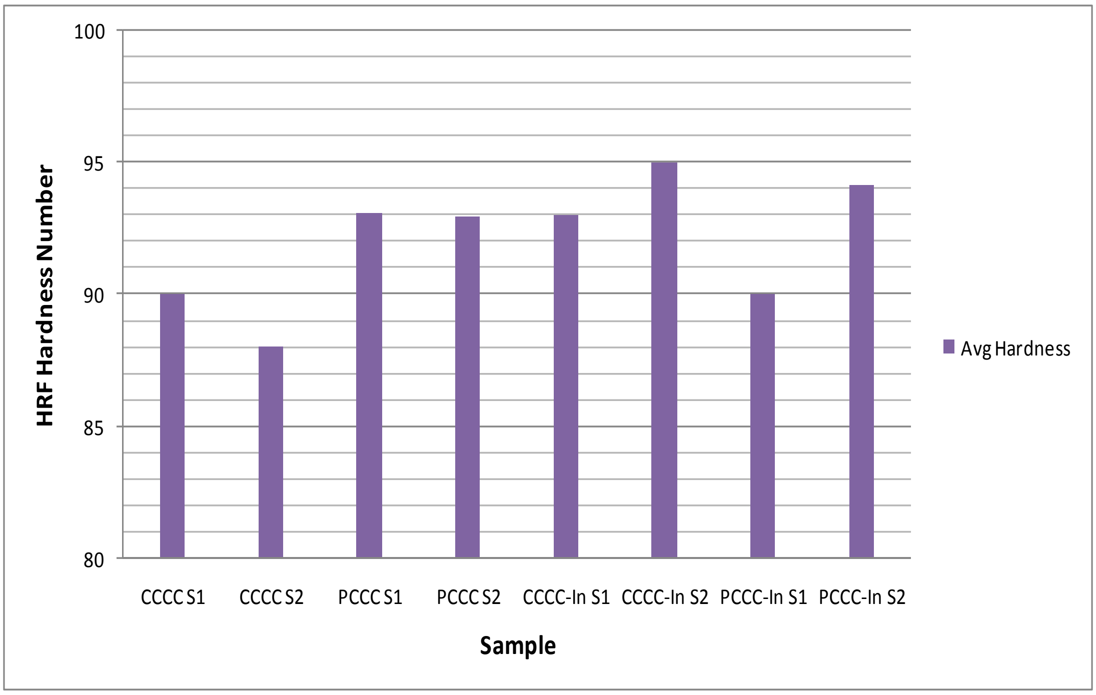


Figure 4.38 Rockwell Hardness for Injection Moulding Parts

Hardness was checked on the injection moulded parts produced with all mould configurations. Figure 4.38 shows the graph of the Rockwell hardness number for parts. The hardness number varied from minimum of 88 to a maximum of 95. The hardness test on these parts showed the variation of hardness was quite low, as indicated by the small value of standard deviation. It was also concluded that the presence of inserts did not impact on the hardness in any consistent manner. This was apparently due to the low cooling rates for the epoxy moulds. Despite the fact that moulds with inserts had quite less cooling times as compared to moulds without inserts, the cooling rate is slow enough as compared to metal moulds and therefore not significant. This is the reason that hardness of the parts produced with different moulds did not differ much.

4.10 Summary

In this chapter, the experimental results for the CCCC and PCCC moulds are presented. The main advantage gained from using epoxy was the ability to produce profiled conformal cooling channels (PCCC) fabricated with RT techniques. These fabricated mould cavities and core were used for the injection moulding experiments for proving the concept of better heat dissipation for profiled channels over circular channels.

Profiles Conformal Cooling Channels (PCCC) and epoxy moulds with embedded conducting thermal inserts are novel techniques for the reduction in the cooling times which leads to the overall reduction in the cycle time for the injection moulding process. The thermal simulations done earlier also verified the enhanced cooling for the above mentioned techniques.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

In this research, a new hypothesis is tested by fabricating conformal cooling channels within the polymer injection moulds using aluminum filled epoxy material. Rapid tooling techniques were used for fabrication of the cooling channels. Contribution of this research is the reduction of cooling time in polymer injection moulds fabricated with aluminum filled epoxy material with the aid of two novel concepts for reducing cooling cycle time. The first concept is the use of Profiled Conformal Cooling Channels (PCCC) in injection moulds and the second concept is the use of embedded conducting metal inserts within the epoxy moulds. The epoxy mould cavities were designed, developed and experimental study was done to check the thermal performance of the moulds.

From the results of this research, the following conclusions are drawn:

1. RP/RT technologies were used to produce an innovative design of Profiled Channels in plastic injection mould tools. This is a novel concept for further reducing cooling times in injection moulding process and reducing the overall injection moulding process cycle time.
2. Another concept for enhancing the thermal conductivity of epoxy moulds was to embed conducting metal inserts within the moulds. These moulds were fabricated using the same mould design as before and embedding an aluminum insert between the cavity and cooling channel during the epoxy casting process. The experimental study of this arrangement of embedded inserts revealed even further reductions in cooling time than moulds without inserts.

3. The combined effect of Profiled Conformal Cooling Channels and embedded inserts further decreased the cooling time in the injection moulding process. The comparative evaluation was performed and it was found through injection moulding experiments that PCCC have about 17% to 19% reduced cooling time than CCCC. The reduction of cooling times for insert moulds was about 50 percent as compared to moulds without inserts.

5.2 Research Contribution

With the conclusion of the current research, the following contributions have been added to the existing knowledge base.

A novel technique is conceived and studied for cooling channels that have a cross section that follows the cavity profile. These cross sectional shapes termed as Profiled Conformal Cooling Channels (PCCC) were fabricated with RT techniques. Experimental and numerical study of these channels showed that PCCC can dissipate heat more effectively than the conventional circular cross-sectioned cooling channels.

The concept of embedding conducting metal inserts within the epoxy moulds is a novel technique for enhancing the thermal conductivity of epoxy material. Due to the low thermal conductivity of epoxy material, the cooling time for molten polymers is quite long.

The advantage of Rapid Tooling for fast fabrication of injection moulds with aluminum filled epoxy can become insignificant due to this property of epoxy. In the current work, this novel idea of embedded metal inserts was studied and experimented. The experiments showed that the cooling times are far reduced in the insert moulds as compared to CCCC and PCCC moulds without metal inserts.

5.3 Future Work

5.3.1 Performance Analysis for Epoxy Moulds

In the current research, polymer injection moulds fabricated with aluminum filled epoxy material was used in a vertical injection moulding machine. The machine is not like horizontal automatic injection moulding machines which can produce plastic parts with repeated cycles and do mass production. This machine is mainly used for prototype production as after every injection, the mould has to be taken out from the machine and the part has to be manually ejected from the mould. In the research, only a few parts were produced for the testing of the thermal performance of moulds with circular and profiled channels.

The moulds with embedded conducting inserts were also used for injection moulding, achieving considerably reduced cooling time for parts produced with circular channels. One hypothesis was concluded that the moulds having conducting inserts may have less thermal stresses due to shorter duration of exposure to higher temperatures. To check this, one recommendation for future work is to design a mould with proper injection moulding parameters and fabricated with epoxy and embedded conducting inserts and fix this mould onto an automatic injection moulding machine to check the performance of the mould as compared with a metal mould with actual injection moulding experiments. Such a performance analysis for the epoxy mould will be beneficial for evaluating the idea of reduced thermal stresses in the mould.

If the epoxy mould with conducting inserts can produce more number of parts that a simple epoxy mould, this can save cost and time as more parts can be produced with epoxy moulds. It is also hypothesis that the mould life could also be improved with increased mechanical stiffness and rigidity of the epoxy mould with embedded metal inserts.

5.3.2 Fabrication of PCCC with other RT Techniques

The concept of PCCC could be further investigated using other direct and indirect RP/RT technologies like

- Laminated tooling
- 3D Keltool
- Selective Laser Sintering (SLS)
- Direct Metal Laser Sintering (DMLS)
- Selective Laser Melting (SLM)

for injection moulds fabrication.

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Journal

Comparative Thermal Analysis of Circular and Profiled Cooling Channels for Injection Mold Tools. Journal of Applied Sciences.

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Prototype Production and Experimental Analysis for Circular and Profiled Conformal Cooling Channels in Aluminum filled Epoxy Injection Mould Tools. Rapid Prototyping Journal.

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Investigation on Surface Roughness of Rapid Prototyped parts built by Multijet Modeling System. National Postgraduate Conference, NPC 2008, March 2008, Universiti Teknologi Petronas.

EXHIBITION MEDALS AND PATENT

GOLD MEDAL in Open Innovation Challenge in 24th Engineering Design Exhibition held from 21st to 22nd October, 2009 in Universiti Teknologi Petronas.

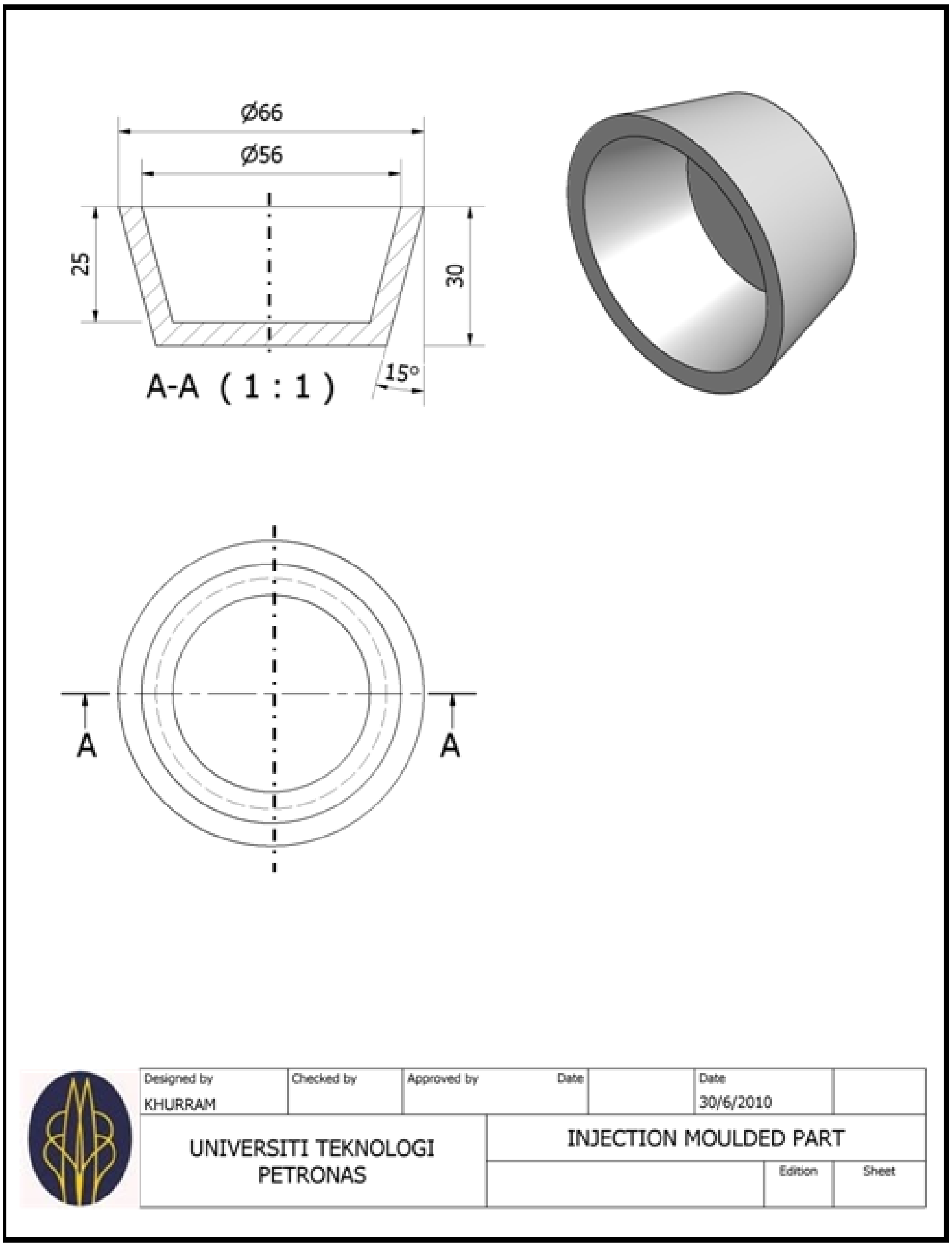
GOLD MEDAL in 21st International Invention, Innovation and Technology Exhibition, ITEX for the invention "Injection Moulds with Conducting Inserts" held from 14th to 16th May, 2010 in Kuala Lumpur, Malaysia.

GOLD MEDAL in Innova Brussels Exposition 2010 for the invention "Hi-Per Moulds", held from 18 to 20 Nov 2010 in Brussels, Belgium.

Patent Filed in Malaysian Patent Office for the invention "Novel Technique for Accelerated Cooling in Epoxy Injection Moulds" with Patent Application number **2010001425**.

Appendix A1

Drawings of Part and Moulds



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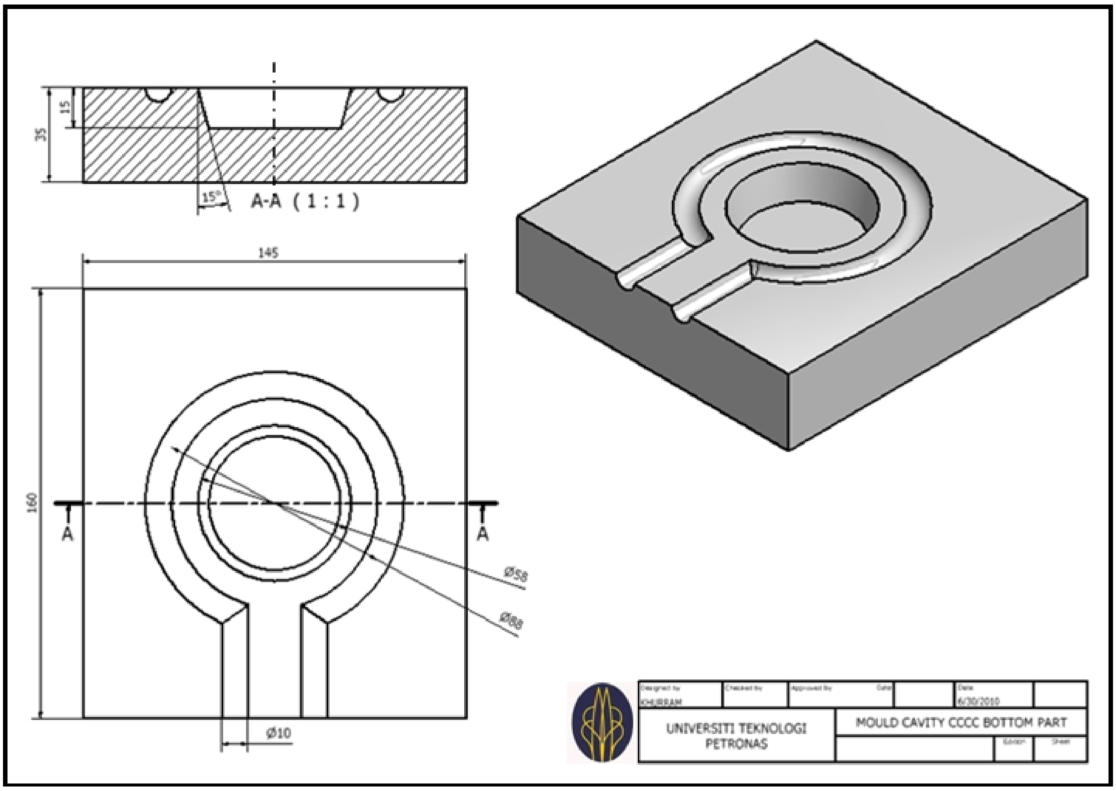
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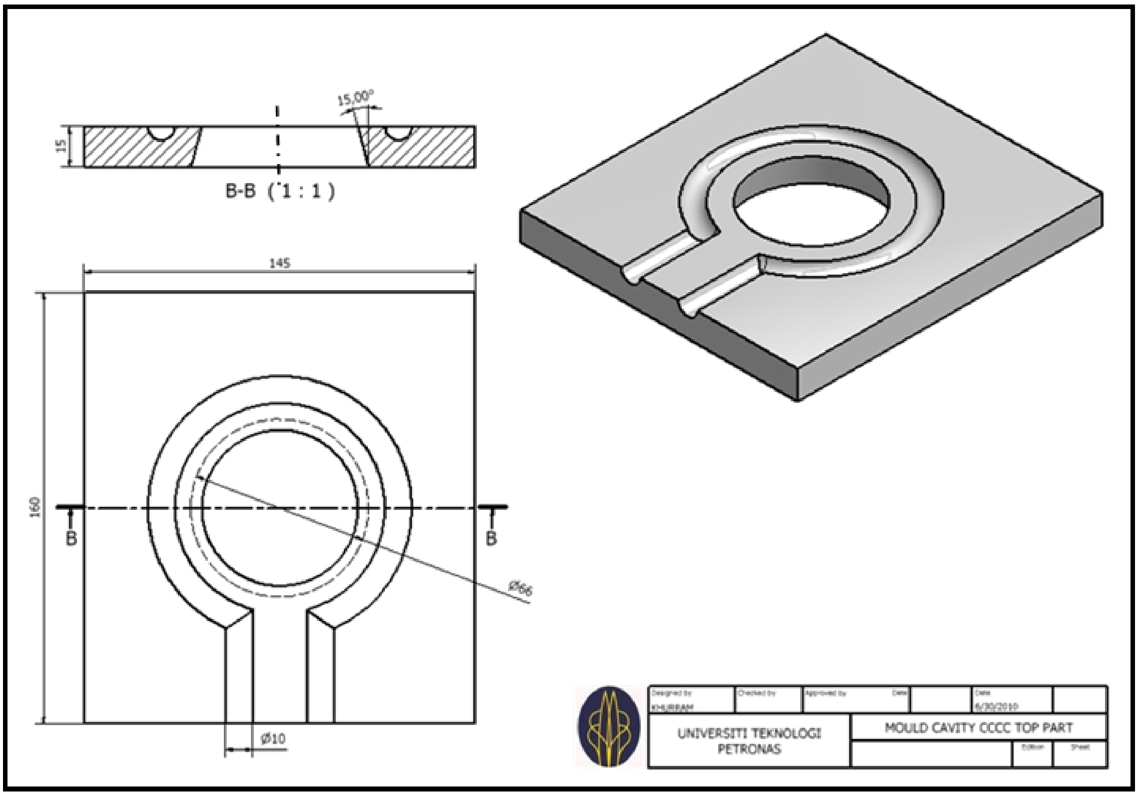

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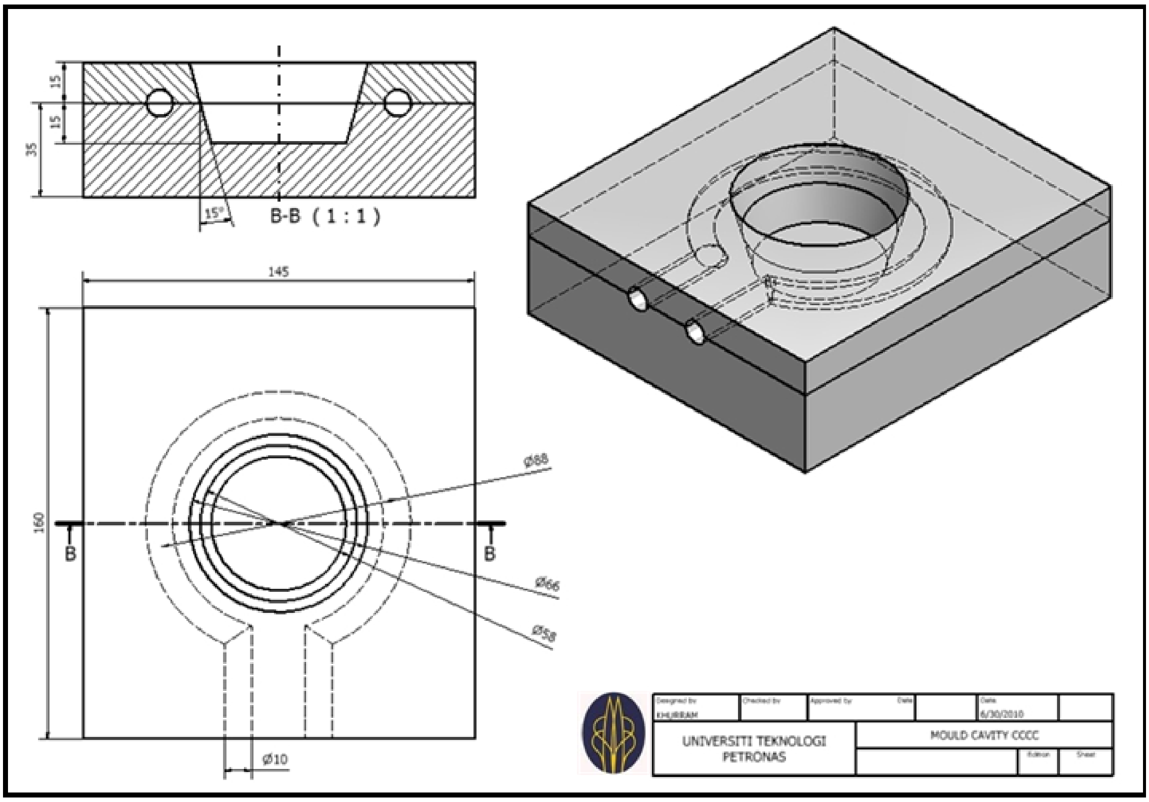
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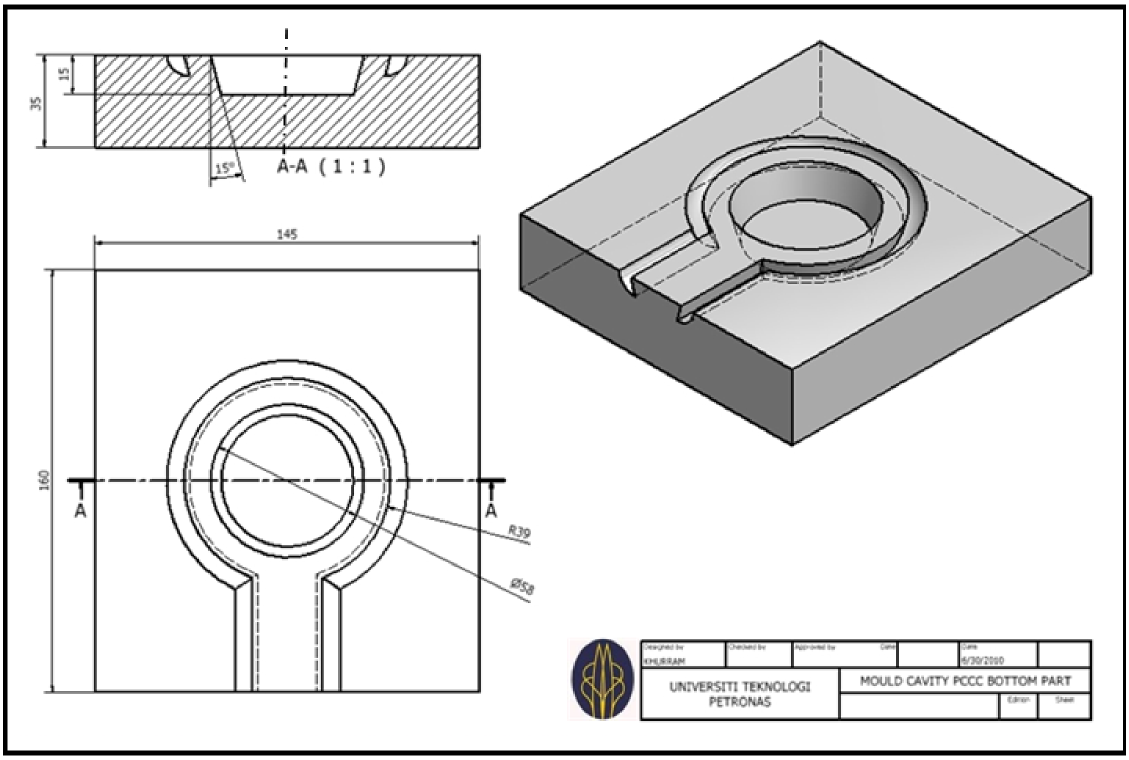
Appendix A5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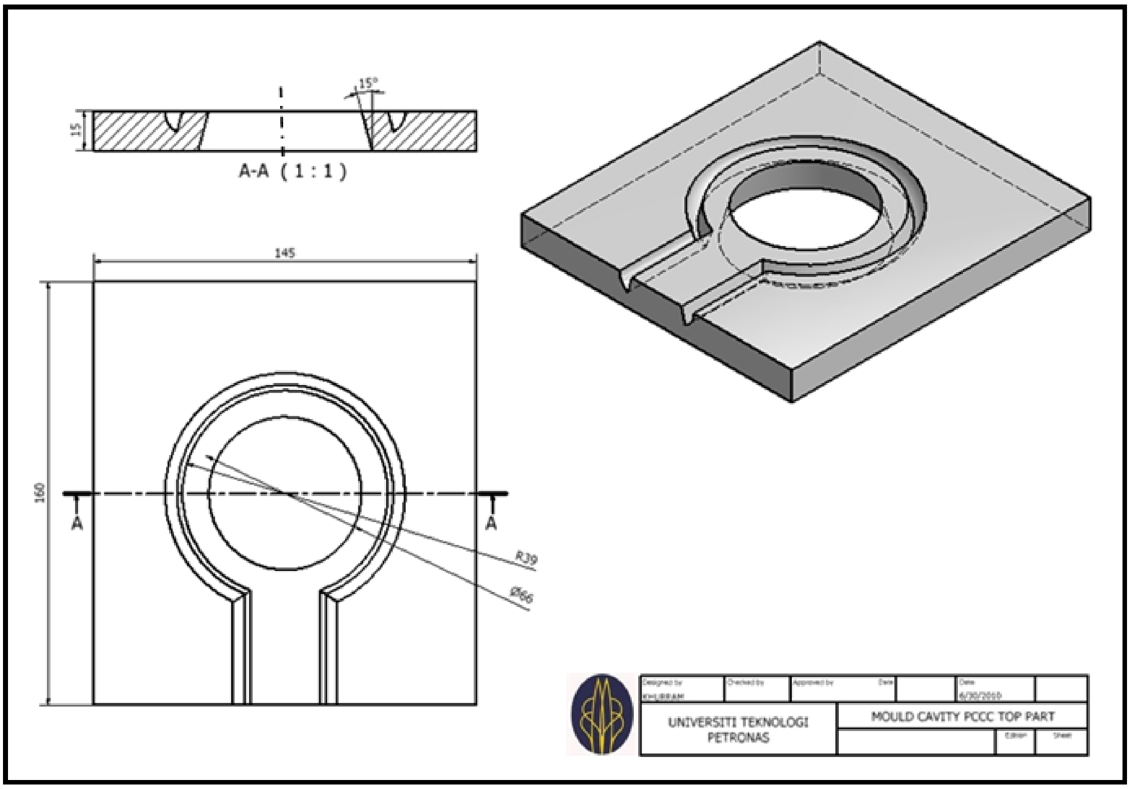
R39
Ø58
Designed by
KHURRAM
Checked by
Approved by
Date
Date
6/30/2010
UNIVERSITI TEKNOLOGI PETRONAS
MOULD CAVITY PCCC BOTTOM PART
Edition
Sheet

Appendix A6


15°
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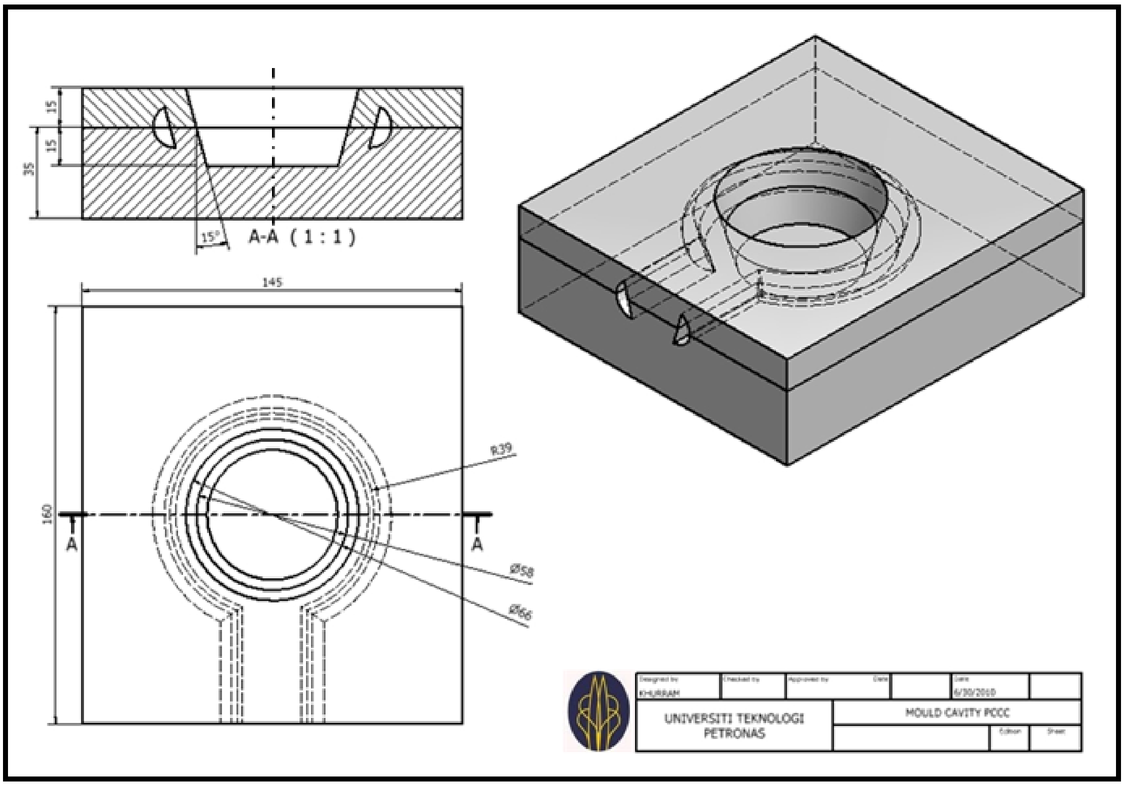
KHURRAM
6/30/2010
UNIVERSITI TEKNOLOGI PETRONAS
MOULD CAVITY PCCC TOP PART

Appendix A7



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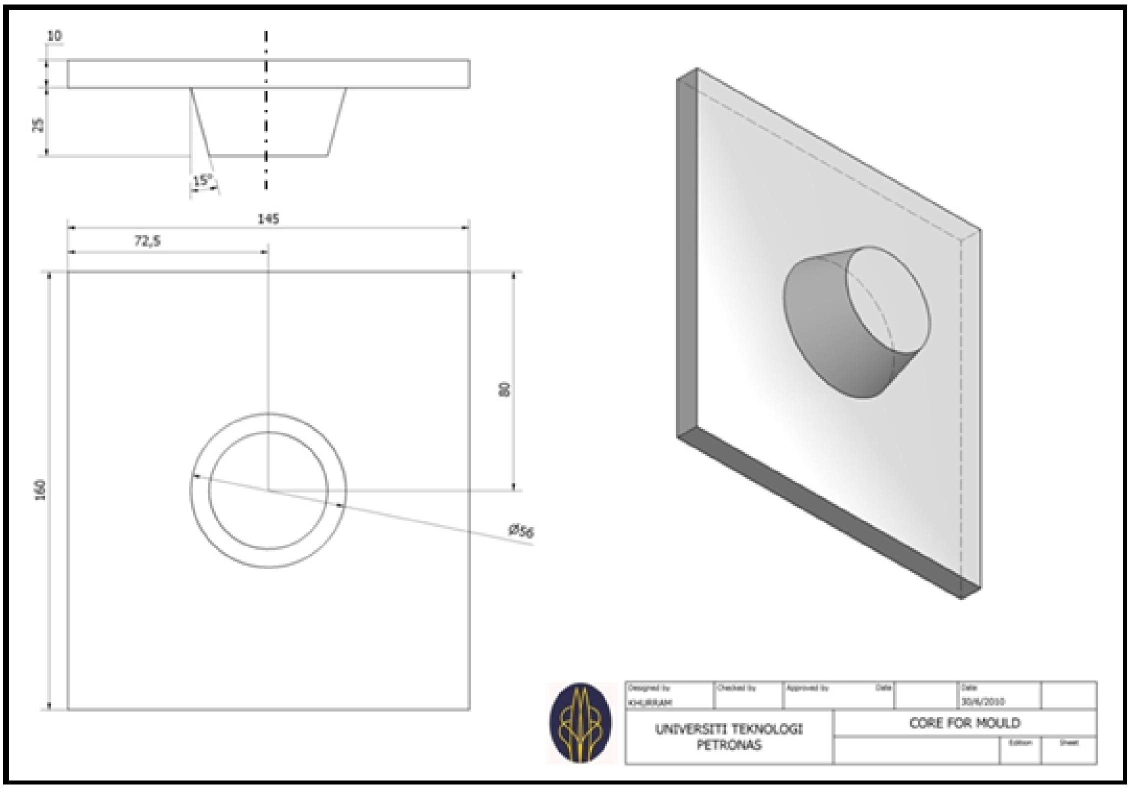
Designed by
KHURRAM
Checked by
Approved by
Date
Date
6/30/2010
UNIVERSITI TEKNOLOGI PETRONAS
MOULD CAVITY PCCC
Edition
Sheet

Appendix A8



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25
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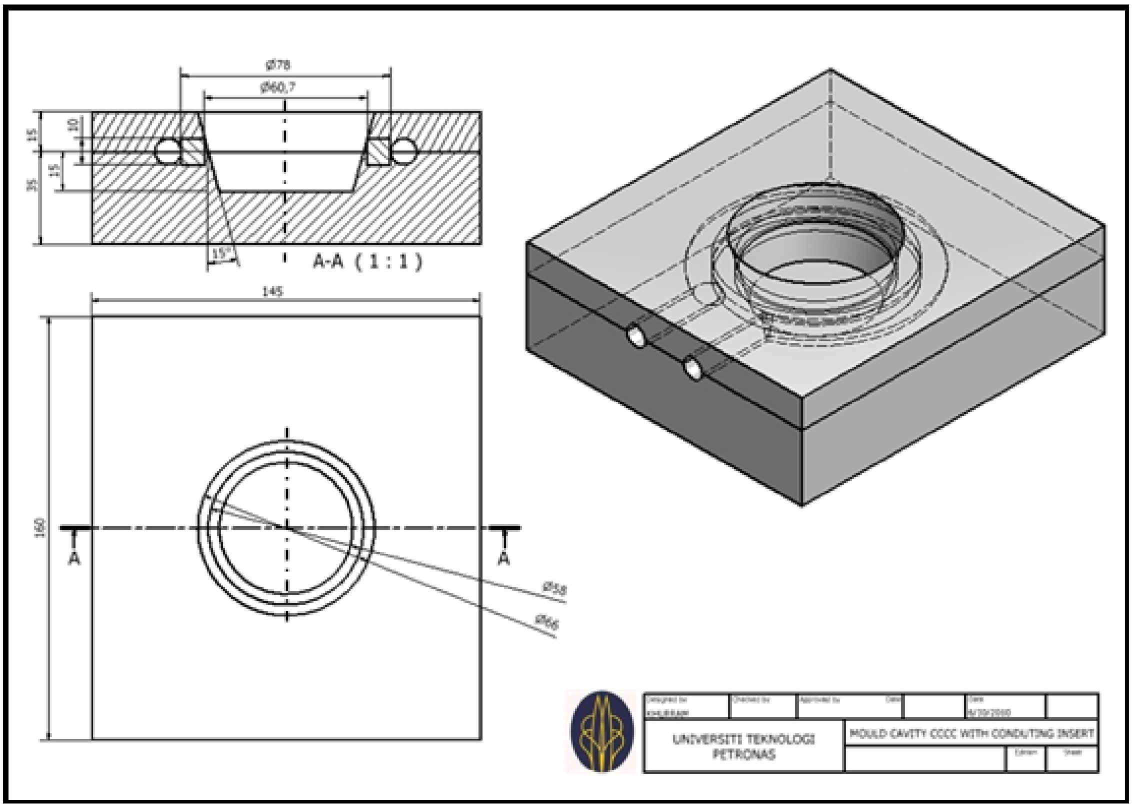
Designed by
KHURRAM
Checked by
Approved by
Date
Date
30/6/2010
UNIVERSITI TEKNOLOGI PETRONAS
CORE FOR MOULD
Edition
Sheet

Appendix A9


Ø78
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A-A (1 : 1)
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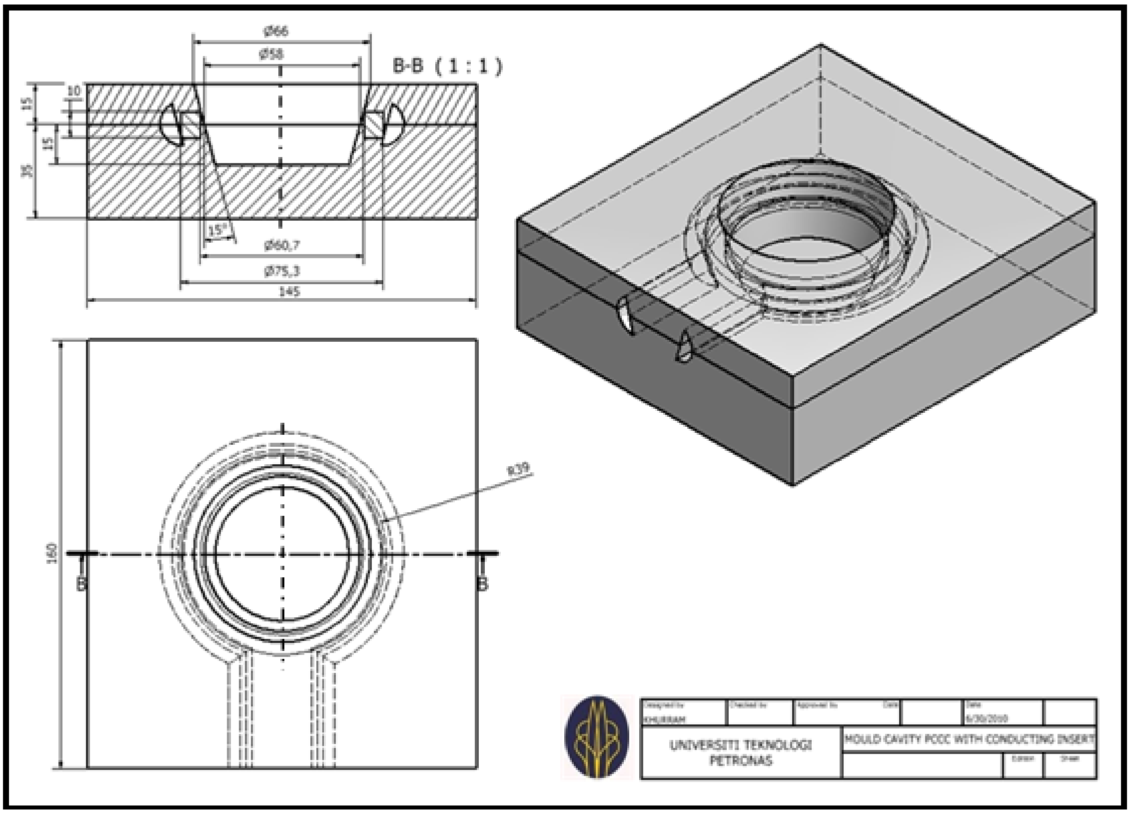
A
A
Ø58
Ø66
Designed by
Checked by
Approved by
Date
Date
UNIVERSITI TEKNOLOGI PETRONAS
MOULD CAVITY CCCC WITH CONDUTING INSERT

Appendix A10



Appendix B

Processing Guide for General Purpose Polystyrene Polyrex PG-22

CHI MEI CORPORATION

59-1 SAN CHIA, JEN TE, TAINAN COUNTY, TAIWAN R.O.C.   TEL: 886-6-266-5000,   FAX: 886-6-266-5555~7

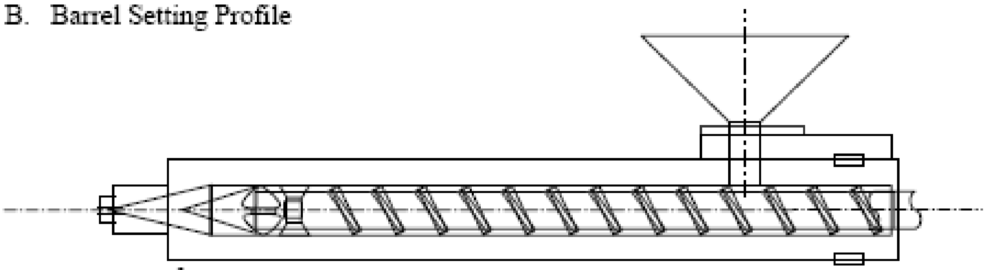
General Purpose PS, POLYREX® PG-22   *V1W*

Processing Conditions

A Pre-drying 80°C x 2~3 hrs

depending on a) Humidity
b) Ratio of reground resin
c) Storage conditions

B. Barrel Setting Profile



MAX(°C)	195	190	170
MIN(°C)	175	170	150

C. Mold Temperature 40~70 °C

depending on a) Thickness
b) Dimension
c) Gate and runner system

NOTE :

1. Keep the resin from dust and contamination during handling and production.
2. Do not retain the hot melt at the barrel for a long time between injection cycles.
3. Temperature setting of manifold system should not exceed 220°C to avoid melt from degrading.

For further information, please contact your local agent or fax to Chi Mei Technical Services Dept. at 886-6-2665555

Appendix C

Calibration Certificate for Data Logger DI-1000TC-8

DATAQ INSTRUMENTS, INCORPORATED

Certificate of Calibration

Certificate Number: 10276112

This certifies that the instrument meets or exceeds all specifications as stated in the instrument's user manual. The instrument has been calibrated using measurement standards traceable to the National Institute of Standards and Technology.

2010-01-27
Calibrated on this day by
Dataq Instruments, Inc.
241 Springside Drive
Akron, OH 44333

DI-1000TC-8
Model Number

1157
Serial Number

CALTEST.EXE REV 1.31
Procedure

JDB
Submitted by

JDB
Tech. ID

DATAQ INSTRUMENTS

CC00001A.FH3

Appendix D

Data logger DI-1000TC Specifications

DI-1000TC Series

Specifications

Number of Channels: Configurable as 4 or 8 channel modules within one enclosure
Supported Thermocouple Types: J, K, T, E, S, B, R - mix and match as required
Thermocouple Input Connectors: Panel-mounted miniature spade, universal TC-type
Temperature Range and Accuracy: See table below.
Open TC detection: An open thermocouple forces the channel to minus full scale.
Cold Junction Sensors: One for every group of 4 or 8 channels, depending upon configuration
Cold Junction Compensation Range: -40 to 125°C
Linearization: Accomplished transparently by the software driver to deliver scale temperature values to the host program.
Input Impedance: >1MΩ
Input Current: <0.05μA
Input Offset Voltage: <5μV
Maximum Normal Mode Voltage: 250VDC/Peak AC momentary; 50VDC/Peak AC continuous
Maximum Common Mode Voltage: 1000VDC or Peak AC
Common Mode Rejection: >160db @ 50 and 60Hz
Channel-to-Channel Isolation: 1000VDC or Peak AC
Input-to-Output Isolation: 1000VDC or Peak AC
Channel-to-Channel Cross Talk Rejection: >160db
Temperature Coefficient: <0.040μV/°C
Digital Filtering: 256-tap comb filter per channel, decimating
Voltage Range: -10mV to 50mV

Expansion Capabilities
Method: Via integral RS-422 port to other DI-1000 Series modules
Max. Sample Rate from Expansion Units: 5 samples/second/channel
Maximum Distance: 4,000 feet

Scanning Characteristics
Maximum Sample Rate: 5 samples/second/channel
Minimum Sample Rate: 0.55 samples/hour/channel
Scan List: 9-position, 8 positions may be programmed for channel number and TC type; ninth position reserved for CJC access
Synchronization: Digital via expansion port to synchronize multiple modules
Sample Buffer: 36 samples

Calibration
Calibration Cycle: One year
Calibration Method: Calibration constants are stored within each module's EEPROM. Provided calibration software to automate calibration in the field.

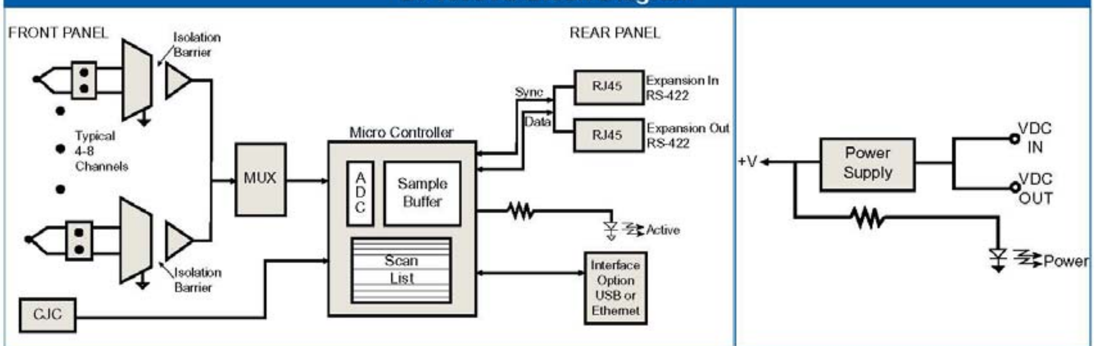
RS-422 Interface

Supported Baud Rates: 9600 (default), 19200, 38400, 56800, 115200
Data Bits: 8
Stop Bits: 1
Parity: None
Handshaking: ModBus protocol
Connector: RJ-45

General

Panel Indicators: Power and Active LEDs
Operating Environment: -40 to +85°C
Enclosure: Aluminum base with steel wrap-around. Aluminum end-panels with plastic bezels.
Dimensions: 5-7/16D x 4-1/8W x 1-1/2H inches 13.81D x 10.48W x 3.81H centimeters
Weight: 20 oz. (8-channel version)
Power Requirements: 9 to 36 VDC, 1 watt

DI-1000TC Block Diagram



Temperature Range and Accuracy

TC Type	Range	Accuracy*	Resolution**
J	-200 to 870°C	±0.3%	0.1°C
K	-200 to 1230°C	±0.2%	0.1°C
T	-200 to 400°C	±0.5%	0.08°C
E	-200 to 660°C	±0.3%	0.2°C
S	-200 to 1760°C	±0.4%	0.4°C
B	-200 to 1820°C	±0.6%	0.5°C
R	-200 to 1760°C	±0.4%	0.4°C

*25°C ambient temperature; excludes CJC errors; excludes TC errors. Value shown is a percent of full-scale range.
**Resolution is for temperatures above 0°C.

Ordering Guide

Description	Order No.
4-channel DI-1000TC 4-channel DI-1000TC with RS-422 interface, for temperature measurement using thermocouples.	DI-1000TC-4
8-channel DI-1000TC 8-channel DI-1000TC with RS-422 interface, for temperature measurement using thermocouples.	DI-1000TC-8
USB to RS-422 adapter	DI-1000-USB
RS-232 to RS-422 adapter	DI-1000-232

DATAQ® INSTRUMENTS
241 Springside Drive
Akron, Ohio 44333
Phone: 330-668-1444 Fax: 330-666-5434
www.dataq.com

Appendix E

Permission from Custom Part

From:	iragolden@gmail.com on behalf of Ira Golden [igolden@custompart.net]
Sent:	Friday, August 20, 2010 3:11 AM
To:	khurram1@streamyx.com
Subject:	CustomPartNet image request

Khurram,

Thank you for your request to use our images. I'm glad you have found them to be informative and easy to understand. You can have permission to use the images of the RP processes in your thesis. Please properly cite the source of the images as having come from www.custompartnet.com. Thank you.

Ira Golden
Product Manager
CustomPartNet Inc.
301-990-1585

Appendix F

ITEX Certificate

MINISTRY OF SCIENCE,
TECHNOLOGY & INNOVATION

ITEX MALAYSIA INTERNATIONAL INVENTION, INNOVATION AND TECHNOLOGY EXHIBITION

MINDS

Certificate of Award

This is to certify that

VIJAY R RAGHAVAN,KHURRAM ALTAF

has been awarded the

ITEX GOLD MEDAL

for the invention

INJECTION MOULDS WITH CONDUCTING INSERTS

at the

21st International Invention, Innovation & Technology Exhibition
ITEX 2010
Kuala Lumpur, Malaysia

held from

14th – 16th May 2010

Academician Emeritus Professor Tan Sri Datuk
Dr Augustine Ong Soon Hock
President
Malaysian Invention and Design Society

MALAYSIAN INVENTION AND DESIGN SOCIETY MINDS

Appendix G

INNOVA Certificate

DIPLOMA

BRUSSELS
Eureka!

THE BELGIAN AND INTERNATIONAL TRADE FAIR
FOR TECHNOLOGICAL INNOVATION

to

Prof Dr Vijay Raghavan
UNIVERSITI TEKNOLOGI PETRONAS

for the innovation
Hi-Per Injection mould

Gold medal

THE PRESIDENT OF
THE INTERNATIONAL JURY

THE PRESIDENT

Brussels, 20th November 2010

Appendix H

EDX Certificate

ENGINEERING DESIGN EXHIBITION

EX 24

Certificate of Appreciation

This certificate is awarded to

Khurrum Altaf

AA 1770 711

for his/her participation in

Open Innovation Challenge

"GOLD"

in recognition of valuable contribution in the twenty fourth edition of

UNIVERSITI TEKNOLOGI PETRONAS'

Engineering Design Exhibition

held from

21st October 2009 to 22nd October 2009

ENGINEERING DESIGN EXHIBITION • UNIVERSITI TEKNOLOGI PETRONAS • EDX PORTAL TO THE FUTURE

Dr. Mohd Fadzil bin Hassan
Chairman
24th Engineering Design Exhibition

Assoc. Prof. Dr Hilmi Mukthar
Director of Undergraduate Studies
Universiti Teknologi PETRONAS