A Study On The Cooling Channels Total Design of Rapid Prototyping Method Using Genetic Algorithms

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ABSTRACT

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Plastic parts are increasing used to substitute metal parts in the worldwide for plastic products have a low cost and high productivity. However, the merit of plastic products will disappear if cooling not enough. Generally speaking, cooling channel is consisted of straight-line cooling channel or cooling channel combination in a mold. This way has a demerit, which is freedom low, and caused uneven temperature distribution on the product surfaces. To resolve this problem, we proposed the block laminated method. This way is use laminated block to create a space with a particular shape in the mold. Block laminated method have some merits, for example, Cooling channel has a high freedom and easy to obtain a uniformity cooling. However, the core block will deform with the cooling channel increase and mold wall decrease, which cause the product defects. At present, for this way there is a problem, which is that there is not a proper method to evaluate surface temperature of product, deformation of mold, and design the cooling channel. So, our research objective is define an evaluation function, discuss the surface temperature distribution, mold deformation and automatic generate cooling channel.

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ラピッドプロトタイピング成形冷却管の GA による設計に関する研究

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樹脂製品は高精度･低コスト･生産性が高いため、工業製品の様々なところに使用されている．しかしながら、成形品表面の温度分布不均一と金型表面の変形が大きい場合は樹脂製品の利点を損なう恐れがある．そこで、成形品表面の均一な温度分布と金型表面の変形を少なくするために、適切な冷却構造を設計する必要がある．一般的に、金型の冷却構造は直線冷却管或いは直線冷却管を組み合わせた構造となっています．しかし、この冷却方法では温度分布の均一化に限界があり、さらに加工時間やコストの増加､複雑な金型の実現困難などの欠点がある.その問題を解決するために、ブロック積層方式が提案されている．ブロック積層方式には次の利点がある．冷却構造の自由度が高い、成形品に沿った冷却構造を持たせることで均一な冷却の実現が可能となり、強度を考慮した構造部設計ができる．しかし､理想的な冷却構造の設計手法がまだ確立されていない.本研究では、評価関数を定義し､成形品表面の温度分布とコアブロックの変形を検討し、冷却管の自動生成することを研究目標としている.

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CHAPTER 1

1.0 Introduction

Injection molding is one of the most powerful, highly productive, versatile and rapidly developing methods employed in polymer processing. Plastic production has been a symbol of modern industry in the past 150 years [1]. Plastic products (Figure 1.1) are used widely in most industries, such as in electronics, machinery, chemical, automobile, architecture, and aviation etc, extending to every part in our daily life. Plastic is light, strong, ductile, multi-colored and easy to produce. The usage of plastics is increasing and new types of plastics are continuing to be developed. This is a result of the excellent material properties of plastic and improved manufacturing technologies.

Figure 1.1: Plastic Products Used in Industry

Many methods are developed to manufacture plastic products. Generally, they can be divided into several basic types, including injection molding, extruding, blow molding, reaction molding, compression molding, fiber reinforced plastics molding, thermoforming, laminations and rapid prototyping [2].

Injection molding is a typical forming method used in manufacturing plastic products, it plays an important role in the plastic industry. It is common to industrial equipment or a home electric appliance made using plastic parts produced by injection molding. Although plastic injection molding is already a matured technology, it does not mean that the technology satisfies the requirements industry developments of today. In fact, injection molding technology is considered as a complex technology which requires extensive knowledge of the material, skills in controlling mechanical, fluid and heat transfer and experiences. Traditionally, practical modeling experiments directly and indirectly prove that designers require a lot of experimental data before developing a new model of injection mold based on the old model. Many mold makers set theirs own design standards based on the database created with years of works under criteria set by the company.

However, in recent years with the variation of industrial structure and new design requirements in plastic products, the injection molding technology is becoming even more highly demanded. Many mold designers and technicians are faced with the difficult task to design their own tools.

The main trends of the injection mold evolution are summarized below.

1. High Precision and Large Products

There was a common view that plastic material is not suitable in making precision parts, however recently components like optical disk, camera lenses, mirrors, etc. are made using plastic material. On optical disk surfaces, the length of pits used for recording the information codes is 0.9μm ~3.3μm for CD (Compact Disk) and 0.4μm ~1.87μm for DVD (Digital Versatile Disk), the depth of these pits are 0.1μm. Furthermore, some high precision mechanical parts like transmission gears and pistons, which were made of metal in the past, can now be made using plastic material (see Figure 1.2) while meeting the same precision or strength demands, reducing both material and production costs.

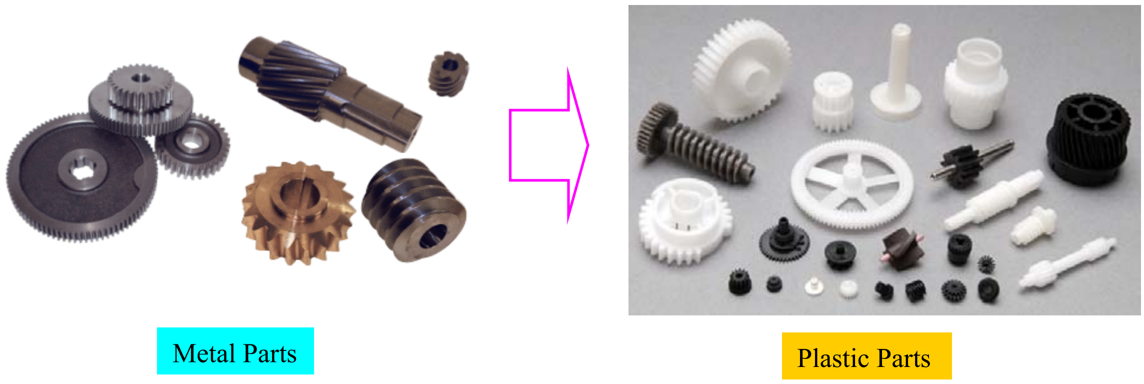


Figure 1.2: Plastic Parts Replacing Metallic Parts

It was a high-risk task molding a large product in the past as a large amount of modification or rework would be required should defect occurred. Trial-and-error mold can be applied for small parts but they are not suitable for large parts. However, the development of computer hardware and CAE technology helps mold designers in finding molding defects before the manufacture. Large products such as car bodies and movable plastic houses, etc. have been produced in practical works; the advantages of large products are obvious, though difficulty exists in the producing the precise product shapes and dimensions.

2. The Enlarging Increasingly Applications and Market of Plastic Products

Plastics replace many products that were once made of metal, wood and ceramics. Products that have gone through the transformation in material include automobile parts, desks and tableware etc. Statistic data [6] shows that there was an average increase of 5.8% demand in plastic products per year from 1990 to 2000 and the trend will continue through to 2010. The car market in Germany [7] is good example of this trend, metrical parts made from plastic increased about 300% while ones made by steel were decreased to only 70% in last 30 years.

3. Information Technology Based on Mold Design and Manufacturing

The revolution of information technology brought with along a series of new developments in most technical fields. Information technology is applied in mold design and manufacturing as a result of significant improvements in computer hardware and software in recent years where powerful and high-speed calculation are now possible. Today, applications such as CAE (Computer Aided Engineering), CAD (Computer Aided Design), and CAM (Computer Aided Manufacturing) have become essential tools in processes involved in mold design and manufacturing, such as product modeling, flowing analysis, heat transfer analysis, automatic mold design, mold making and injection control etc [9],[45].

4. Quick Delivery, Low Production Cost and Complicated Shape Products

Quick delivery means shorter design and manufacturing time. From electronic devices such as mobile phones, personal computers, to automobiles and machineries parts, quick delivery has become the new target in the industry. Also, the design and manufacturing time of injection molds (“mother tools”) have to be shortened and at the same time, the production cost has to be lowered to prevail in strong market competitions.

In recent years, products with complicated shapes are increasing, production speed became more efficient as more than two molds, sometimes even three molds, are combined into one.

Complicated plastic products can reduce the number of tools used for molding but increasing difficulty of design and molding.

5. Application of High-End Technology in Injection Molding

High-end technology refers not only to tools like CAD, CAM and CAE technologies, but also the process of controlling, scheduling, management, design and manufacture technology in building an enhanced technology system. Researchers have attempted using high-end technology a few years ago, however there is quite some time before high-end technology becomes a widely practical application. There is though a growing need for a modernized and efficient production solution like high-end technology.

The above trends leads to significant changes in traditional plastic products and injection molding technologies, in particularly, high precision, large size and complicated shapes will be the new key product features and aim for molding technologies. This means there is a demand for new research and development on mold design and manufacturing technologies that satisfies the new requirements of plastic production today, which includes higher precision, quick delivery, high quality and low cost.

The study below aims to design a suitable cooling system which can be powered by uniformity cooling, it using a numerical calculation method to estimate the size, layout and shape of cooling channels during design. Although CAE software can be employed to provide numerical analysis molds designs, however due to the various shapes of cooling channel and manual designs, requires extensive design experience and substantial trial-and-error procedures to accurately determine its size, layout and shape. This ineffective procedure entails high design costs hence more effective measures are called for. There are other research groups who have developed a cooling channel, which is optimized by genetic algorithm, however they were more interested in obtaining the optimum layout, size, and cooling condition parameters of cooling channel in the injection mold rather then one which satisfies modern requirements mentioned above.

1.1 Overview on Plastic Injection Mold

Injection molding is a process of the manufacture plastic products, which integrate the technologies of mechanics, thermodynamics, control, fluid flow and material. Injection molding process has many complicated environmental variables [22]. Researches are working to improve the productivity and formability of this process.

Concrete operations and resin material etc can be processed with injection molding, which's procedure includes drying, transport, heating, filling, packing, cooling, ejection, and post-process procedures. Usually, the injection molding process consists of four major stages – filling, packing, cooling and ejection. The shape generation of product is completed in the packing and cooling stages, which are conducted inside the closed molds. Resin state is the transformation from fluid state to solid state as heat application is reduced.

1.2 Research Overview

Table 1.1 lists the principal molding defects and their causes. From the summary we can understand, a large percentage of molding defects are caused by heat related factors, which is why heat handling or temperature control is an important factor to focus on.

Table 1.1: Molding Defects and Their Causes

Molding Defects	Description and Causes
Warpage	Different temperature distribution between two sides of product Improper ejector locations
Wall Slant	Uneven temperature distribution on product surfaces Poor cavity and core structure design or improper locations
Sink Mark	Sudden variation in wall thickness Uneven temperature distribution on product surfaces Poor gate of runner design
Short Shot	Mold temperature is too low Poor gate design Product wall thickness is too small Air gap failure
Burn Mark	Impurity in the resin materials Excessive frictional heat generated during injection
Flash	Clamping force is too small Impurity on product surfaces Poor precision of parting line
Flow Mark	Mold temperature is too low or improper cooling

Weld Line	Poor gate location design Mold temperature is too low Air gap design failure
Ejecting Trouble	Poor gate or runner design Product taper is too small Bad ejecting timing Mold structure design errors
Shrinkage	Incorrect or insufficient injection points Variations in product thickness Uneven cooling

A faster cooling speed is desirable in production though it has the potential to cause the product precision failure thus creating defects. This problem is more obvious in high precision molding. It is important to design a method, which arranges cooling channels in mold in an ideal way so an efficient product cooling and minimum mold deformation can be achieved. To solve the cooling channels design problem in injection molds, it necessary to take a look at the practical methods on applications and the related researches. The following discusses the current design state in this field and problems with traditional methods and former studies.

In practice, many mold design books or molder's manual provide concrete design criteria based on principles or former design experience. They usually provide a set of the design rules and corresponding product measurement for cooling channels design. Usually, mold technicians use these design rules going without a second thought. These rules may be applied successfully in general mold designs, however, without accurate and reasonable theoretical explanations, these experience-based rules will be limited to a high level exertion like precision mold designs. Another important issue is the evaluation of the cooling performance in injection molds, which is carried out both in the mold design stages and practical molding stages.

Finite Element Method (FEM) is a popular tool used for injection mold design. Many software of mold design such as Patran, Moldflow, 3-D Timon [41], are adopting to accurately predict the heat state in molds. Boundary Element Method (BEM) had to be used in analyzing the surface temperature on the mold cavity [15],[16],[17].

In molding processes, the evaluation of the product cooling state usually uses the overall cycle time and the molding quality of the products. The former item is relatively simple, the shorter the cycle time, the higher the efficiency. The latter is more complicated, as it involves the product appearance, size and deformation state.

Injection molding is a technology that depends heavily on experience. Conventionally, the method of trial-and-error is used for improving product quality. But recently, with the higher precision and complexity is required, the traditional method is becoming more costly and time consuming. Therefore more and more researches are conducted on improving product quality and reducing the time of formation. Up till now, researches of cooling channels design are mainly based on improving the cavity temperature distributions.

Cavity surfaces and their surrounding area are the main places that affect the transcription property of molding. As injected melted resins are closed inside the cavity, cavity surfaces are the only places through which the resin can transfer its heat to mold sides. In recent years, various methods have been developed to improve the thermal property of cavity surface. A method using thin films of stainless layers to stick on the cavity surface and heating with electric current to control the temperature was developed. Another method using infrared radiation assistance to improve the accuracy of injection molding parts was proposed. Other methods which try to improve molding quality include filling the compressed air into mold cavity and heating the surface in a short time. As the main feature of these kinds of methods is the direct execution of operations on cavity (resin) surfaces, it is very efficient in improving the resin flow and the speed of solidification. However these technologies are quite complicated and require additional equipments. These technologies are only good for molding high precision products with simple shapes such as optical disks and not suitable for products with complicated shape that uses the common molding.

Besides the direct operations on mold cavity surface, many studies are conducted to accurately arrange the construction of cooling channels so the heat transfer state can be balanced with the thermal state in the mold. Researchers tested several types of copper alloy with different thermal conductivity in the mold cores while comparing their cooling effects - their basic processes were the first to be simulated using the analysis software (Moldflow). The hypotheses were verified using molding experiments, the results indicate that with the increase of thermal conductivity in the core materials, the temperature distribution became more uniform and the cycle time could be reduced. To estimate the cooling effect, thermal analysis data and the data on temperature variance on core surfaces gained by thermocouples were utilized. Also, improved formability and cycle times were reported in methods, which have heating and cooling systems going through cooling channels.

Most typical cooling systems have cooling channels consist of several straight line cooling channels or rearrangement of them [4], [18], [19], as shown in Figure 1.3.

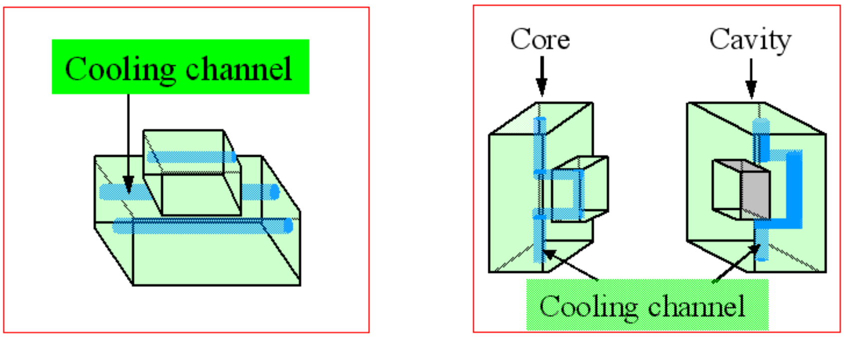


Figure 1.3: Line Channels and Their Combination

With the coolant flowing continuously, heat is transferred out of the mold though it is difficult to maintain an appropriate temperature field for even cooling in the mold using these cooling methods. The complexity of the mold cooling system increases as new molded products may demand even more functions and higher precision. An effective solution of this problem would be automatic arrangement methods that consist of a combination of curved cooling channels and straight cooling channels with an optimum length and located in suitable positions. This method should vary the shape and locations of cooling channels automatically according to the heat distribution in the mold area.

A numerical calculation method is used to estimate the size, layout and shape of the cooling system during design so uniformity cooling can be achieved. Although CAE can be utilized to conduct numerical analysis, however the calculation of size, layout and shape is still a difficult task, as it requires extensive design experience. Thus, it is impossible to achieve a suitable and effective design due to various shapes of cooling system and manual designs based on the professional designers' experience, trial-and-error procedures are still needed. Trial-and-error entails a substantial design costs as a result of inefficient design procedures. Although research groups also reported on cooling system optimized by genetic algorithm, they were only interested in obtaining the optimum layout, size, and cooling condition parameters of cooling channel in the injection mold.

The cooling effects were confirmed by molding experiments carried out using rapid prototyping. Rapid prototyping is a process that is capable of converting a 3D-CAD design into a physical object by means of layer-by-layer powder, solid or liquid-based manufacturing methods. These technologies are also called “layered manufacturing” or “solid freeform fabrication”. In mechanical and manufacturing engineering, rapid prototyping is the process of building prototype objects to evaluate whether a proposed design is meeting the requirement in terms of shapes, sizes, fit and form, functionally and other requirements. It enables feasibility studies of the product and assists in locating manufacturing problems early in the design phase. This greatly reduces costs and the time-to-market of product. Managers, engineers, surgeons, architects, artists and professionals from many disciplines commonly use current rapid prototyping systems.

Among these are selective laser sintering (SLS) as shown in figure 1.4, fused deposition modeling (FDM) and Laminated object manufacturing (LOM) as shown in figure 1.5, 3-dimensional printing (3DP). Each of these technologies and the other rapid prototyping process has their own advantage and disadvantages, however their basic fabrication concepts are very much similar.

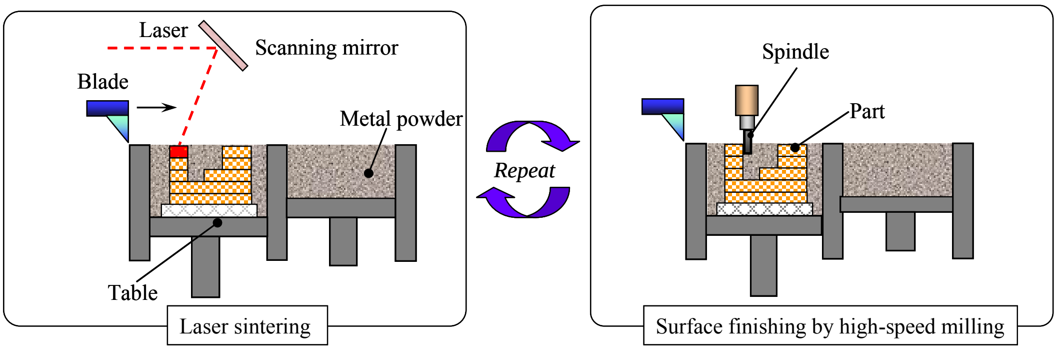


Figure 1.4: Concept of Milling-Combined Laser Metal Sintering

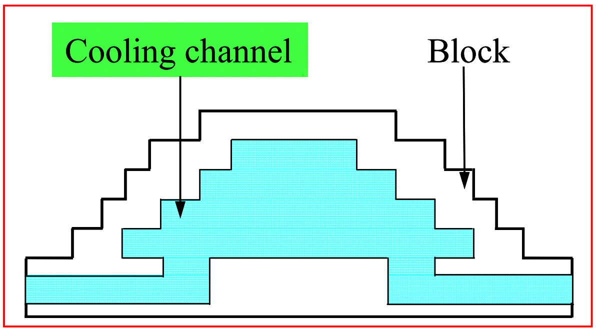


Figure 1.5: Block Lamination Mold

The comparison results of a high cooling core and low cooling core shows that when cooling channels were arranged close to the heat Concentrate area, the temperature peaks were dropped and the product deformations in warpage were reduced. However, despite the efforts in researches of heat related designs, it is still not yet sufficient to master heat handling in injection molds. The aim of these researches is to realize rapid and precise designs while reducing human decisions as much as possible. Therefore, clear and dynamic design criteria based on theoretical design methodologies are crucial as well as user-friendly design procedures.

Cooling uniformity is often used in estimating whether mold cooling was successful though the results vary according in different cases with no clear explanation. Therefore, it is important to have a good conceptual description of the heat state in order for its variations to be precisely evaluated, thus precisely controlling the temperature within the injection mold at where it is needed.

1.3 Problem Statement

During the review of current cooling channel related designs in plastic injection molds in section 1.2, a few issues were identified, these are summarized as follows:

1. The evaluation methods used in product surface temperature measurement, mold deformation and the generation method of cooling channels are vague. Methods such as measuring the temperature at different points in the mold surface, judging the product appearances, or the measuring of product deformation are concrete means used in practical cases, however they lead to inconsistent evaluations of mold cooling related designs and replicas using the same design rules in a new mold design are difficult.

2. There is various design criteria used in cooling channels in injection molds and most of these are not theoretically proven. The experience based design criteria or design rules are applicable only in limited number of injection mold types where similar technical features exist, however they cannot be applied to advanced mold design such as high precision, large mold design and new design cases easily. Therefore design criteria based on the commonly applicable theoretical principles are still necessary.

3. Current design methods and procedures for cooling channels design in plastic injection mold are not clear and uniformed. Many of them are applicable for concrete design cases or targets and other problems under special conditions. These methods are difficult to be reused in common design cases, thus leading poor design efficiency, even the design failures on molding productivity and formability. Clear evaluation based standard design methods are essential in the realization of cooling channels optimization in injection molds.

1.4 Aim of This Study

In response to the problematic cooling channels generation in plastic injection molds, this study focuses on three major aspects:

1. Find a uniform evaluation method for cooling channels designs used in injection molds which can reflect the resin solidification state. Evaluation should be base on the resin solidification process. As well as that, evaluation method should be supported by theoretical knowledge rather than just the practical experience. A unified evaluation standard used in injection molds is the essential condition for the cooling channel design and the know-how and design principles can be applied to other design cases also.

2. Propose a clear design criterion which is based on the evaluation of mold instead of the concrete based design criteria. This is the next step in the concept and evaluation standard stated in previous items; it is an important application of concept and evaluation standards in mold designs.

3. Provide an evaluation based design procedure for optimum design for cooling channels in an injection mold. This is the concrete way of realizing proposed design criterion by operating heat related elements in injection mold. The contents include automatic design of cooling systems and their corresponding procedures.

To handle the cooling channels design problems, this research takes the following basic rules into consideration.

In this research, a definition of temperature error of an arbitrary point on resin surface is defined as the temperature difference between the point and the average value of all points on this surface at a moment in time during the cooling. Then the dispersion of all points on the resin surface is calculated, the result represents the cooling uniformity on resin surface at the moment. For example, smaller value in the calculated result means less temperature errors occurred. With the consideration of all the dispersion values from the beginning to the end of the cooling process, an evaluation function is defined using both spatial factors and temporal factor are defined.

By comparing the values of the evaluation function derived from the current use of cooling channels, the cooling effect can be examined. Also by changing the layout of the cooling system in the mold, different evaluation values can be obtained. The proposed method will be applied to minimize the evaluation value automatically; the smallest value obtained would be the optimum design of the cooling channels in molds. With the optimization of cooling channel designs, the mold would achieve even cooling in the resin solidification process.

1.5 Thesis Structure

This thesis has been organized in 7 chapters whose contents are outlined as follows:

Chapter 1, the current chapter, is a general overview on the background and the issue involved in cooling system design in plastic injection mold, states the objective of the study and briefly illustrates the resolution for the issues.

Chapter 2 provides a literature review composed of three major sections. First is an overview of cooling channel design technology in plastic injection mold. Next is the explanation of cooling channel design method using Genetic Algorithm. Finally is the analysis of advantages and disadvantages of this method.

Chapter 3 presents the methodology used in this study. It firstly explains the block laminated method and its merits, then it goes to explain the genetic algorithm application. Finally it resolves the issue of designing a cooling system in a plastic injection mold. The basic method is to use the evaluation function as a governing function to change the cooling channels generation in an injection mold. Automatic design of the cooling channels is provided. By automatic design cooling channels, the cooling uniformity of product will be improved to reduce the impact of unbalanced heat, and the same time decrease the deformation of the mold in order to realize good product productivity and formability.

Chapter 4 illustrates the applications of the proposed method and procedures used in conducting the automatic generation of numerical analysis on the cooling channels. The case studies are conducted based on two dimensional or three dimensional symmetrical mold models. The main discussed cases include automatic generation under the condition of random cooling channels shape with shape restrictions of initial shapes. The outcome of temperature distribution and deformation distribution will be reported.

Chapter 5 illustrates the applications of the proposed method and procedures used in conducting the automatic generation of numerical analysis on the cooling channel in sprue bush. The case studies are conducted based on two dimensional or three dimensional symmetrical mold models. The main discussed cases include automatic generation under the condition of random cooling channels shape, cooling channels shape, and without cooling channels in the sprue bush. The outcome of temperature distribution will be reported.

Chapter 6 is a report of experiment used to verify the proposed theory and related methods in molding tests. Practical molding is carried out using sprue bush plastic products and a manufactured injected mold. According to the experiment results, the features and the difference in the cooling channels are compared and the difference between numerical analysis and actual molding are discussed.

In chapter 7, a review of research goals, which provides a summary of the results obtained from the investigation, is presented. Also recommendations and suggestions for future research in this area are stated. Figure 1.6 shows the structure of this thesis.

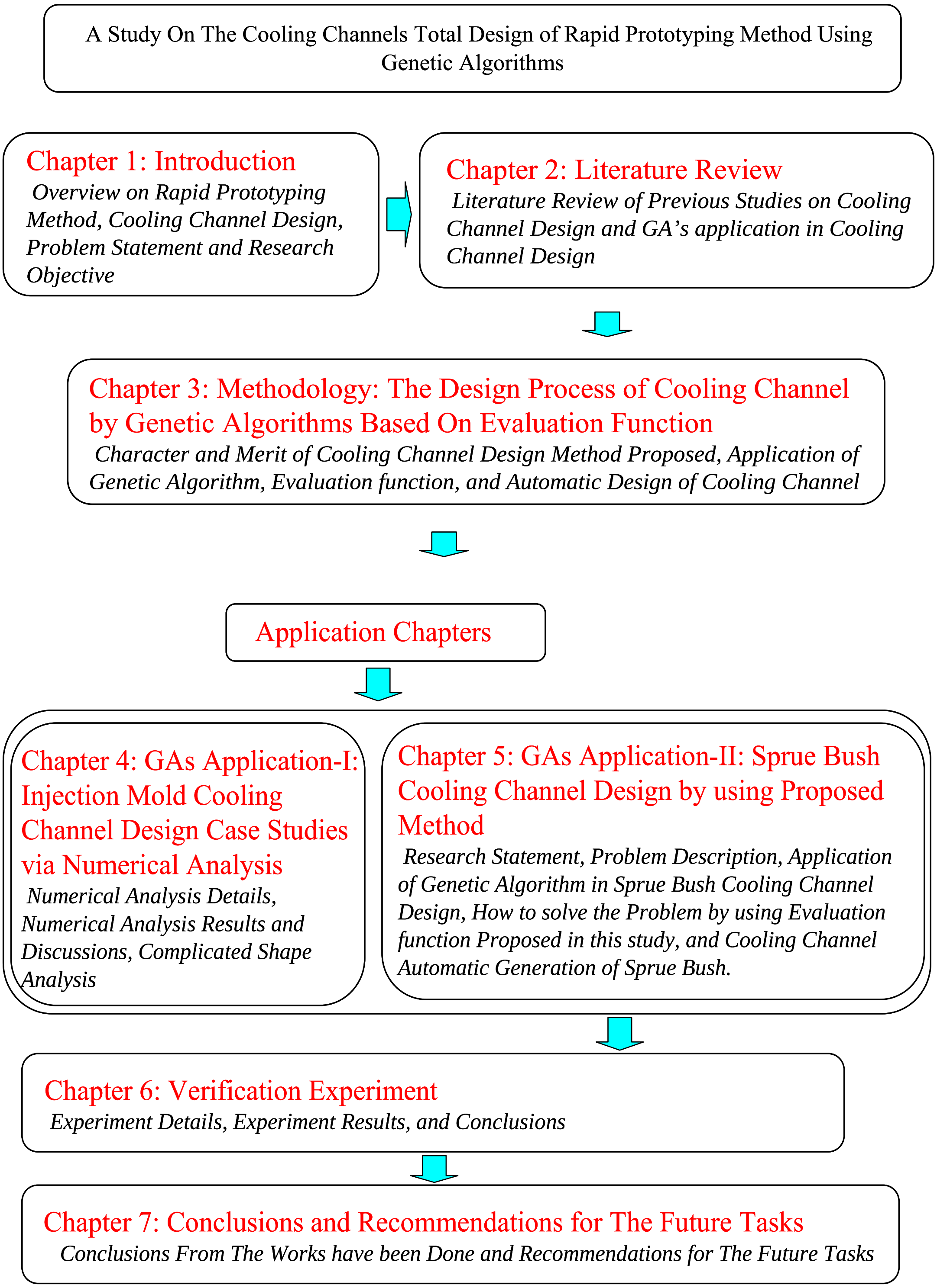


Figure 1.6: Structure of the Thesis

CHAPTER 2

2.0 Literature Review

2.1 Cooling Channel Introduction

The demand of plastic products, such as molded by the plastic injection molding, is increasing every day [29]. Plastic products are used widely in many industries (Figure 2.1). Injection molding remains the most popular method for producing precision plastic parts of various shapes with complex geometries at low cost. The plastic injection molding process is a cyclic process. There are four main stages in this process (see Figure 2.2), they are close mold, filling, packing and cooling, and ejection. The plastic injection molding process begins with feeding the resin and the appropriate additives from the hopper to the heating/filling system of the injection molding machine. This is the “filling stage” in which the mold cavity is filled with hot resin melt at high injection temperature and pressure. After the cavity is filled, additional melted resin is packed into the cavity at a higher pressure to compensate the expected shrinkage as the resin solidifies. This is followed by the “cooling stage” where the mold is cooled through the cooling system until the product is sufficiently rigid to be ejected. The last step is the “ejection stage” in which the mold is opened and the product is ejected, then the mold is closed again to begin the next cycle.

It is well known that more than three-fourths of the cycle time in the injection molding process is spent on cooling the hot resin melt sufficiently so that the product can be ejected without any significant deformation [30],[54],[55].

Figure 2.1: Plastic Products Used in Different Fields

In plastic injection molding, one of the serious problems is the generation of residual strain and stress caused by non-uniform solidification of plastic materials. Cooling rate of the injected plastic is slower than that of metal because of low heat conductivity of plastics. The differences of cooling rate produce different molding shrinkage and internal residual stresses, which cause defects such as warps and cracks in the plastic molded products a few years after the molding. Generally, if the plastic materials are cooled down uniformly and slowly, the generation of residual stresses will be very much reduced [21]. However, the cooling time should be short taking manufacturing cycle time into account. It is important to control the temperature distribution and the layout of the cooling pipe, coolant temperature and coolant flowing speed. Factors to monitor in the plastic injection mold in order to control the temperature distribution and the cooling rate are cooling pipe layout, coolant temperature, and coolant velocity and mold temperature. The
generation of residual stresses can be reduced by manipulating these factors.

The role of the cooling system in a plastic injection mold is to provide thermal regulation in the injection molding process. When the hot plastic melt enters the mold impression, it cools down and solidifies by dissipating heat through the cooling system channels. During the filling and post-filling stages of the injection molding, a solid layer is formed along the walls as the hot molten resin touches the cold molding walls. As the material cools down, the solid skin will thicken as the cooling continues until the entire material solidifies. Efficient cooling is very crucial in obtaining high productivity and formability in the process. The cooling system also plays an important role in obtaining high product quality. A cooling system that provides uniform cooling across the entire product ensures product quality by preventing differential shrinkage, internal stresses, and mold release problems. The design of the cooling system should also consider the manufacturability of the system in order to control the cost of mold construction. The cooling stage accounts for more than three-fourths of the total cycle time of the injection molding process, the simulation and analysis of the filling process is complicated.

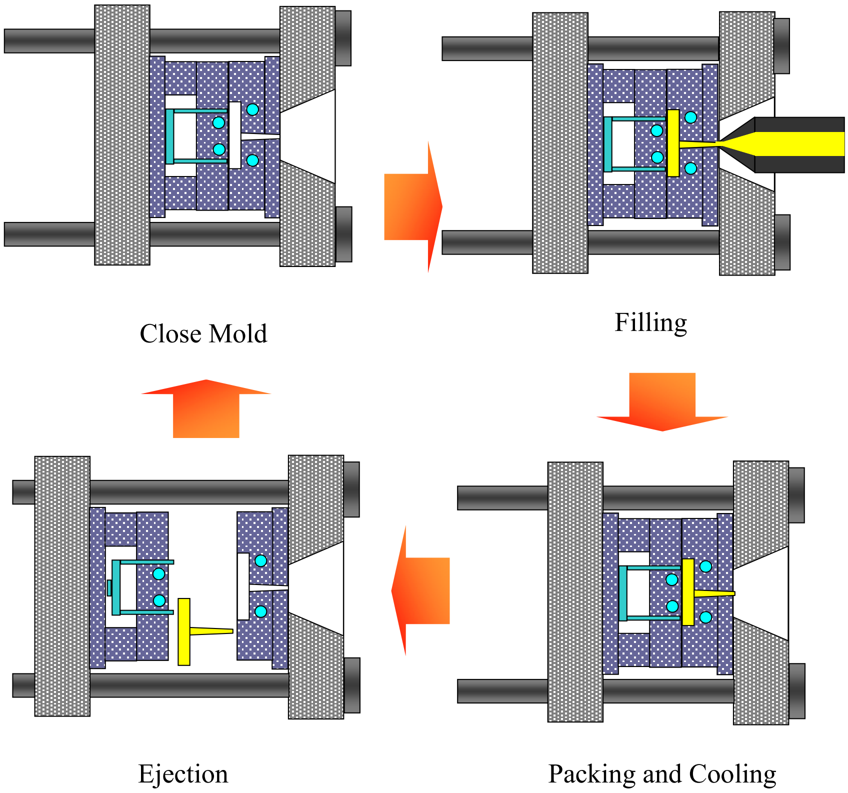


Figure 2.2: The Plastic Injection Molding Process

Computer aided engineering (CAE) [20] is implemented to predict defects before manufacturing the plastic product. CAE is also utilized to save on cost and to optimize the conditions of injected material and cooling process. Many researchers have studied the cooling conditions using CAE in order to reduce manufacturing defects. Matsumoto have presented a design sensitivity formulation for steady-state heat conduction problems. Lam have explored an approach to optimize both the cooling channel design and the process condition selection simultaneously through Genetic Algorism (GA). Hasan have proposed a warpage optimization method adopting a response surface constructed by using finite element analysis results based on analysis of variance method. Li have studied a methodology to optimize cooling channel size, locations and coolant flow rate for a multi-cavity injection molding die in the two dimensional field. In these researches, the cooling pipe layout consists of only straight lines. However, the plastic injection mold with complex cooling channels can be produced by a stereo lithography system of metal powder. Xu and Koresawa have suggested design methods composed of complex cooling channel. Matumori have taken into account the cooling pipe layout design by numerical, and the effects of a coolant flow and a coolant temperature change in a cooling pipe is the same as the effect of temperature distribution in the mold during the cooling process. Cooling channels studies of mold are as follows:

2.2 Straight Cooling Channels or Their Combination

Cooling of an injection mold is crucial to the performance of the product, influencing both the rate of the process and the resulting quality of the product. However, generally cooling channel designs and manufacture have been confined to relatively simple configurations, primarily due to limitations of the manufacturing methods and the lack of a design methodology appropriate for cooling channels. General cooling system in a mold involves a straight-line cooling channel or combinations of channels arranged as shown in Figure 2.3 [57]. As the drilling of these cooling channels are restrained by the product ejector system limit, the size and number of cooling systems are difficult to define in many cases. With the demand for increasingly complicated molds, the manufacture of cooling channels will become more and more difficult.

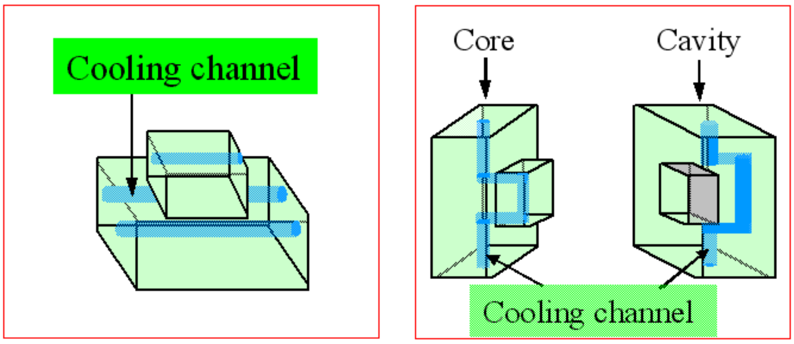


Figure 2.3: Line Channels and Their Combination

2.3 Curve Cooling Channel

Uneven cooling of a process in a mold will generate various molding defects. In order to solve these problems, the curved cooling pipe in the molding is proposed. The mold with curve cooling pipe can be manufacture using Selective laser sintering (SLS) method.

Selective laser sintering is an additive manufacturing technique that uses a high power laser (for example, a carbon dioxide laser) to fuse small particles of plastic, metal (Direct Metal Laser Sintering), ceramic, or glass powders into a mass representing a desired 3-dimensional object. The laser selectively fuses powdered material by scanning cross-sections generated from a 3-D digital description of the part (for example from a CAD file or scanned data) on the surface of a powder bed. After each cross-section is scanned, the powder bed is lowered by one layer thickness, a new layer of material is applied on top, and the process is repeated until the part is completed.

Compared to other methods of additive manufacturing, SLS can produce parts from a relatively wide range of commercially available powder materials, including polymers (nylon, also glass-filled or with other fillers, and polystyrene), metals (steel, titanium, alloy mixtures, and composites) and green sand. The physical process can be full melting, partial melting, or liquid-phase sintering. Plus, depending on the material, up to 100% density can be achieved with material properties comparable to those from conventional manufacturing methods. In many cases large numbers of parts can be packed within the powder bed, allowing high productivity.

SLS technology is widely used around the world for its ability to easily generate complex geometries directly from digital CAD data. While it began as a way to build prototype parts early in the design cycle, it is increasingly being used in limited-run manufacturing to produce end-user parts. Another less-expected and rapidly growing application of SLS is its use in art.

SLS process is to create complex mold for injection molding plastics products. Firstly, the software models the prototype to be made. The system then slices the parts into cross-sectional data. After that, the powder-leveling mechanism lays a thin uniform layer of powder. The material is then bonded by laser thermal fusion; the unbound powder remains for support. Finally, another layer of loose powder is deposited and the process is repeated until three-dimensional solid object is completed.

The flow chart of 3D data generation of cooling channel and the example of 3D curve channels generation process are shown in Figure 2.4 and Figure 2.5 respectively [58]. As a result, distributing the cooling channels where heat flows concentrates helps make the mold and molded resin temperature uniform. This in turn decreases the warp and increases the shape precision of the work piece. Increasing mold and resin cooling time decrease the injection cycle time.

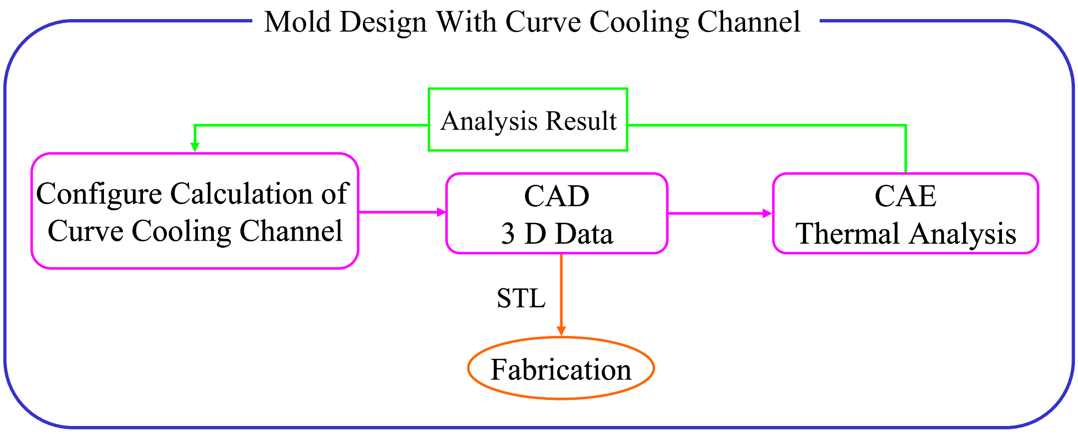


Figure 2.4: The Flow Chart of 3 D Data Generation

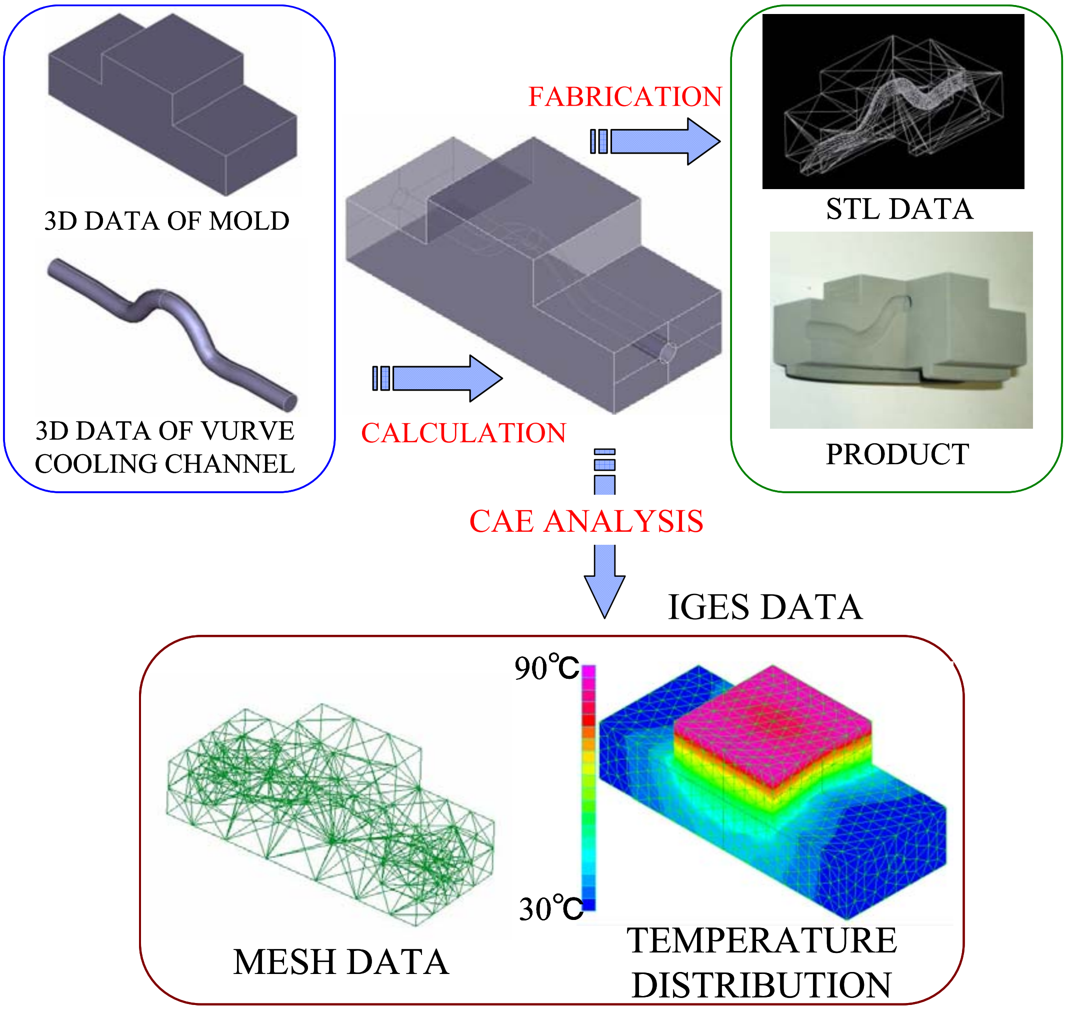


Figure 2.5: The Example of 3D Curve Channels Generation Process

2.4 **Optimization Cooling Channel**

2.4.1 Elements Move Method

To improve formability and productivity in injection molding, cooling channels should be designed properly because temperature distribution on the cavity surface affects formability and productivity of injection molding and this distribution is dependent on the layout of cooling channels. A number of research activities had been carried out to estimate temperature distribution in injection molding, some advanced technologies founded from these theses were incorporated into computer-aided engineering (CAE) and are used widely to design injection molds and their cooling channels.

However, a proper layout of cooling channels cannot be always designed despite such advanced technologies. Despite advanced technologies such as CAE, the design of the cooling channels layout is still has to be done manually, the efficiency of the design is dependent on the experienceand knowledge of the molding designer.

A methodology is required to generate effective layouts of cooling channels automatically, to implement the desired temperature distribution on cavity surface in the injection molding and to evaluate the potential effectiveness of the methodology.

This section discusses the complexity of the cooling channel design especially aspects which require sophisticated data handling as compared to traditional algorithmic procedure. It also describes details of the methodology developed by this study to date with emphasis on its autonomous system approach.

2.4.1.1 Basic Concept and Problem Definition

Basic concept: Automatic design of cooling channels should naturally include the estimation of temperature distribution on molding surface and the arrangement of cooling channels as its indispensable functions. As correlation exists between the temperature distribution on molding surface and the layout of cooling channels, the temperature distribution is influenced by the layout of cooling channels. It happens, however, that the layout of cooling channels cannot be concluded without evaluating the temperature distribution, and the decisions in rearrangement of cooling channels depend on the temperature distribution of molding surface affected by the layout of cooling channels on that occasion. Also, it could be possible that the layout of the cooling channels is redesigned when the temperature distribution on molding surface is identified to be inadequate.

The process of cooling channels design proceeds with decisions made for determining a layout of cooling channels under assumptions on many factors that ought to meet technological constraints due to the physical and geometrical requirement of the injection mold to be designed. Decisions based solely on algorithmic evaluation would be too exhaustive because its evaluation would become complicated and the dynamic phenomena as the temperature distribution of mold affects the determination of cooling channels layout, whereas the layout of cooling channels controls the temperature distribution of mold. Decisions would be a trial-and- error type procedure with repeated reassessments.

Therefore, it is rather realistic, at least in the automatic cooling channels design, to assume that decisions would be made by cooling channels themselves mainly based on their own reasoning under the temperature distribution of mold formed by those of cooling channels, and partially referring to the results of algorithmic analysis that the system is prepared to perform for instance in CAE analysis. By this prescription, the state-of-the-art technologies formerly developed could be incorporated into the automatic cooling channels design. Some of the simple and heuristic decision-making may be formulated into this decentralized autonomous type system that would perform for finding a proper cooling channels layout autonomously without getting too involved in an exhaustive search and without the help of skillful molding designer.

2.4.1.2 Problem Definition

Definition of the problem is "to develop a software system that autonomously designs an effective layout of cooling channels for the injection molding". The term "effective layout" refers to the arrangement of cooling channels concluded by realizing desired temperature distribution on the molding surface. The term "autonomously" refers to designing the system without external control, and that the system has capabilities modify its corresponding to changes in design specifications and requirements. The correlation between the evaluation and the determination plays the important role for the system to be developed.

2.4.1.3 Preliminary System Design

Specific methods have been proposed in this section including elements such as:

(1) Cooling Element

(2) Source Element.

Both of these elements are fundamental components of the system. Initial locations of cooling channels by a set of Cooling and Source Elements are shown in Figure 2.6. Cooling Element is used to remove heat from a cavity surface and to move away from the present location towards another location by responding to the data received from several Source Elements. Source Element is an evaluator which is in charge of steering the Cooling Elements. Source Elements are located on the cavity surface for delivering the information to Cooling Elements as the thermal condition on the cavity surface is to maintain the desired distribution previously determined. The thermal condition on the cavity surface is analyzed by using the CAE assuming heat-transfer to be steady-heat conduction for the arrangement of Cooling Elements located according to the specified layout of cooling channels.

A methodology is presented to automatically generate an autonomous cooling channels layout for which heat transfer of the domain is assumed to be steady-heat state conduction in this paper. By Source and Cooling Elements interacting mutually with each other, the suitable arrangement to realize the desired objective temperature can be obtained automatically. The following conclusions are drawn:

(1) A cooling channel is modeled by a set of several Cooling Elements in the mold moving to find an appropriate location by responding to the data received from the Source Elements on the cavity surface. Design changes can be dealt with using these elements mentioned above.

(2) The essential number of cooling channels to remove heat from molded part can be estimated by setting up any number of channels at initial condition.

(3) This method is able to deal with three-dimensional cooling channels arrangement in a mold.

Changes in cooling channels shapes and arrangements are shown in Figure 2.7 [59]. This method is able to determine the ideal arrangement for cooling channels, if the objective temperature and the tolerant temperature on the cavity surface are specified individually and ideally for giving consideration to productivity and formability in injection molding.

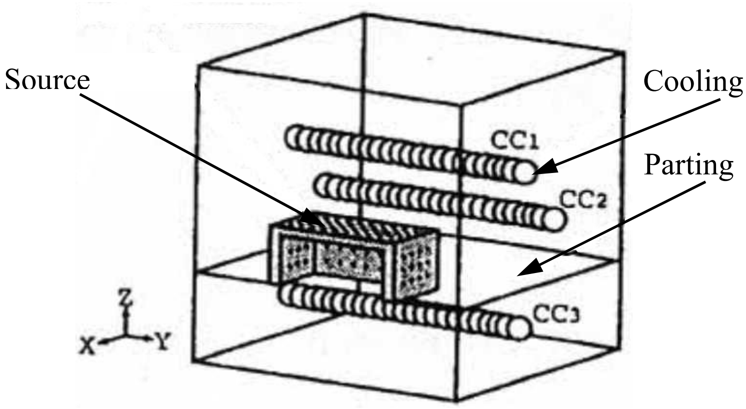


Figure 2.6: Initial Locations of Cooling Channels by a Set of Cooling Element and Source Element

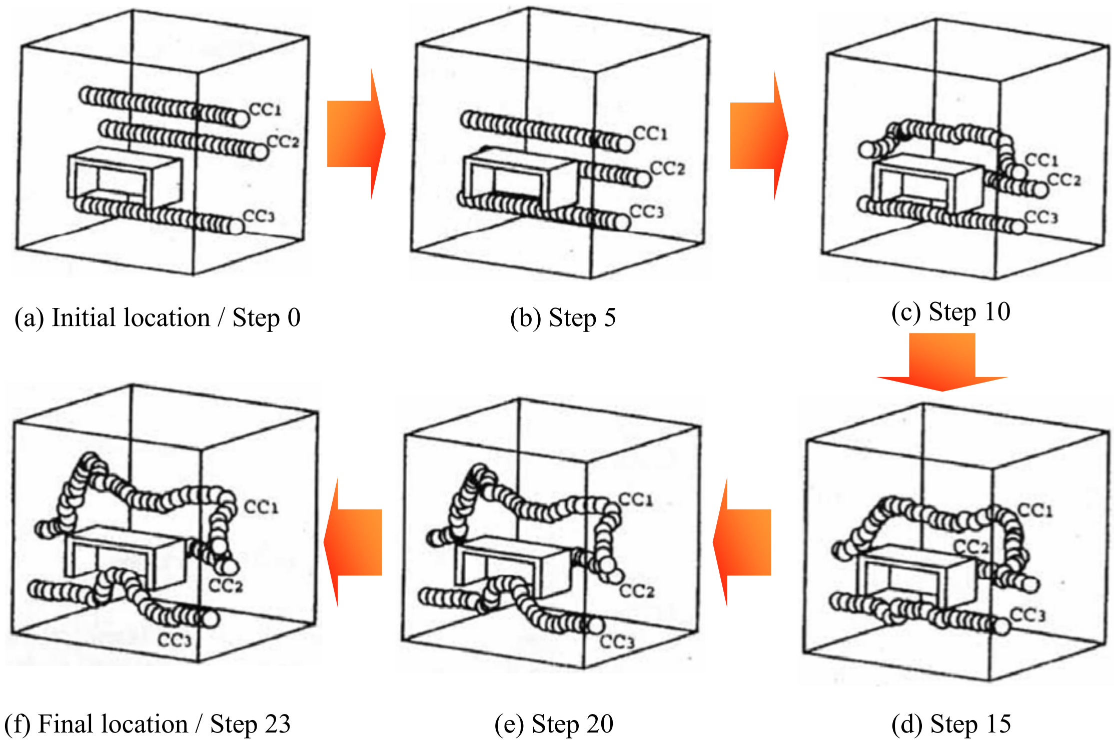


Figure 2.7: Change of Cooling Channels Shape and Arrangement (Step 0～23)

2.4.2 Basis Vector Method

Recently plastic products, such as electronic products, automobile parts, office automation equipments and precision equipments, are used widely in our everyday life as they can be easily molded into complicated shapes. Complex shapes are formed using injection molding, which is one of the typical and major processes of plastic molding.

In plastic injection molding, one of the issues is the generation of residual strain and stress caused by non-uniform solidification of plastic materials. The cooling velocity of plastic is slower than that of metal because of low heat conductivity of plastic. There are differences in cooling velocities affected by temperature gradient. They produce different molding shrinkage and the internal residual stress, which causes warps and cracks in the plastic molded products some years after the molding. If the plastic material in the gel state of the solidification process is controlled well and is cooled down uniformly, the generation of the residual stress can be reduced much.

The objective of this section is to simulate the cooling process of plastic moldings by adjusting the location of cooling pipes and cooling rate, and to find out the proper cooling methods and conditions for the molding products. The simulation of the cooling process of plastic moldings requires fluid-thermal-solid coupled analysis to analyze a field concerning interactions with different coupled fields. In the engineering field, thermal, fluid and structural coupled problems can be found and they are one of the most important issues to be solved these days.

In this research, finite element method (FEM) is used to separate coupled field. Then, plastic flow in the injection molding process is simulated using general-purpose finite-element and the cooling process in a mold is simulated by developed finite element. A simple analysis model of the plastic injection mold is determined, and then the system will try to optimize the new shape and position of the cooling pipe in the model.

2.4.2.1 Generation Method of Simulation Model

The final goal of this research is to optimize cooling pipe system in the plastic injection mold. This design problem is realistically a shape optimization problem. The objective is set the average temperature of a surface shared with plastic product. Also the shape and position of cooling pipe are taken as the design variables. When the numerical optimization method is applied to this shape design problem, the basis vector method is adopted to decide the shape and position of the cooling pipe in order to reduce the number of design variables.

The basis vector method can control the mesh warping c to the boundary shape changes during optimization. When the basis vector method is applied to the shape design problems, an original shape vector and basis vectors are prepared. Generally, a new coordinate G is generated from the following equation,

$$G = G_0 + \sum_{i=1}^{n} \alpha_i (V_i - G_0) \quad (2.1)$$

where G_0 is the original shape vector, V_i is the basis vector, n is the number of basis vectors and α is the design variable, respectively.

In this study, the new shape vector is calculated from following equation,

$$G = G_0 + \sum_{i=1}^{n} COEF_i \sum_{j=1}^{non} V_j \quad (2.2)$$

where $COEF_i$ corresponds to α_i and V_i to $(V_i - G_0)$, respectively. And the value of $COEF_i$ is changeable ranging from -1.0 and 1.0.

2.4.2.2 Procedure of Optimization

In this study, the response surface method is adopted to construct approximated polynomials to implement effective optimization. At first, the response surface consists of orthogonal polynomial with the design variables of basis vector is calculated by using the orthogonal array L9(3^3) of the design of experiment. Then calculations of 9 design points are carried out. The proper design variables are obtained by the optimization using the response surface by the mathematical programming. The simulation model and the optimization shape are shown in Figure 2.8 and Figure 2.9, respectively [60].

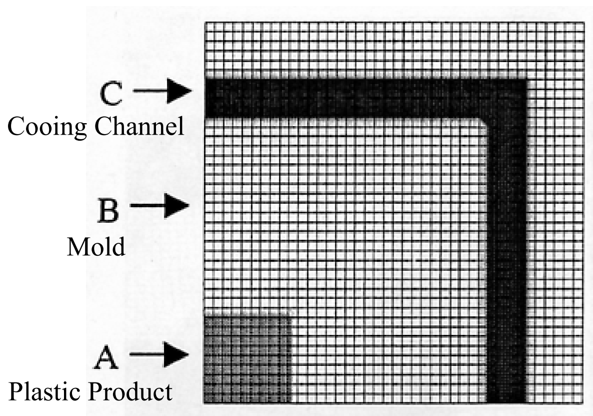
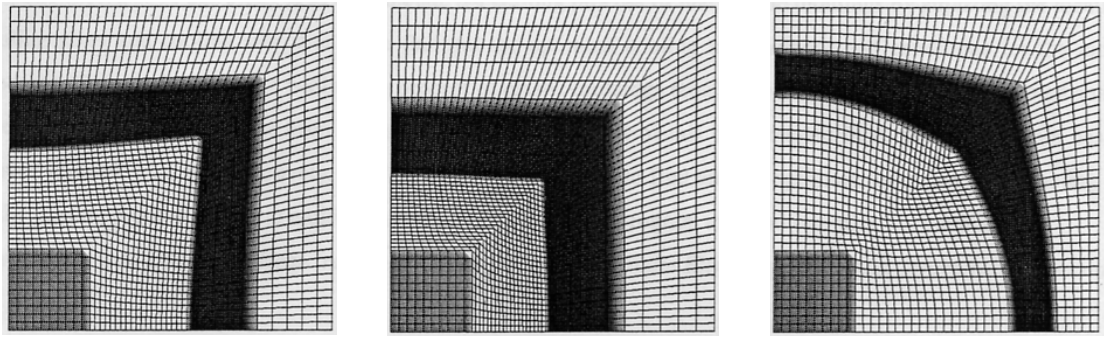


Figure 2.8: Simulation Model



(a) Optimized Shape (b) Examples of Simulation Model

Figure 2.9: Shape Optimization Result

In this study, the basis vector method is applied to make the optimization model of simple cooling pipe system. The response surface consisting of orthogonal polynomial with its design variables is constructed by using the design of experiment. Then the optimum shape of the simulation model is obtained by optimizing the response surface. These processes show the capability of this shape optimization of cooling pipe system.

2.4.3 Cooling Channel Design by GA

Researches have been conducted on optimizing cooling channels designs in the mold by using GA.. GA has a merit of dealing with separate optimization problem as the combine continual variable design of channel diameter and the discontinue variable design of channel position based on the best of survival theory. Cooling channel design by using GA is described as follows [61]:

Firstly, they generated an initial value for design parameters in the possible fields randomly (shown in Table 1). The mold region used for boundary element analysis and the bit length of each gene are shown in Figure 2.10 and Table.2, respectively. The encoding occurs where decimal design parameters are translated into binary variables. The corresponding relationship between the design variables and the chromosome is shown in Figure 2.11.

Secondly, each individual in the population is evaluated and arranged according to their fitness value. Next, a percentage of individuals with high value are forced to stay into the next generation as elite individuals. As for other individuals, crossover or mutation is executed, and offspring is created for the next generation.

In the end, one must design if the convergence condition could be satisfied or not. If the convergence condition is satisfied, the calculation can be finished. Else, they will have crossover and mutation again, the cycle will be repeated again until the convergence condition is satisfied.

As a result, changes of location diameters of cooling channels, temperature of coolant before and after optimization can be shown in Figure 2.12.

The conventional design procedure based on a manual trial-and-error approach is time consuming and it requires extensive human interaction which can be biased. This type of experience-based design approach is not efficient to design products satisfying complex requirement in the highly competitive world. Optimization design technique of cooling channels by using GA is becoming more and more popular amongst designers in deal the complex product designs.

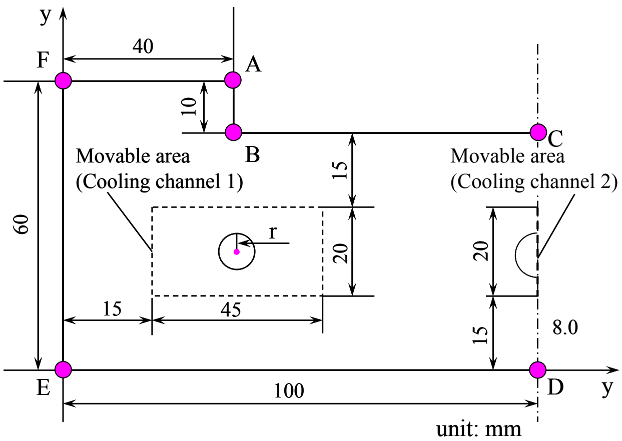


Figure 2.10: Mold region used For Boundary Element Analysis

Table 2.1 Initial and Optimum Values for Design Parameters

	Channel No.	r [mm]	x [mm]	y [mm]	h [W/m²k]	T [deg]
Initial	1	3.01	15.2	15.2	2693.4	8.0
	2	3.01	100.0	17.9	2693.4	8.0
Optimum (76th)	1	3.13	6.0	22.0	3002.1	19.8
	2	3.13	100.0	22.0	3002.1	19.8

Table 2: Bit Length of Each Gene

	Parameter					Sum
	x_1	y_1	y_2	r	T	
Chromosome length	16	15	15	12	12	70

Design variable	Binary number	Chromosome
r_1 =3.01 ⟷	110···1010	
x_1 =15.2 ⟷	111···0011	⟷ 1100000···0000000
y_1 =15.2 ⟷	111···0011	
T_1 =8.0 ⟷	100···0000	

Figure 2.11: Corresponding Relationships between the Designs Variables and the Chromosomes

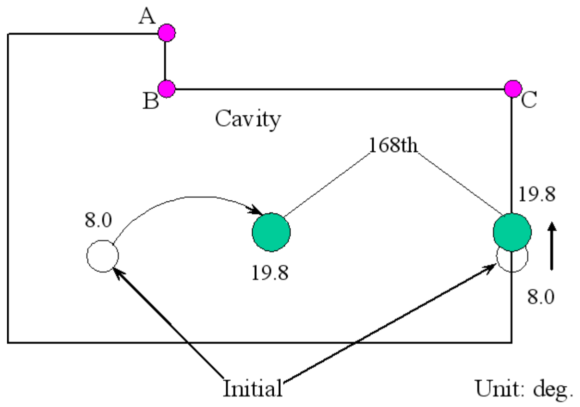


Figure 2.12: Changes of Location Diameters in Cooling Channels, and the Temperature of Coolant Before and After Optimization[4]

CHAPTER 3

3.0 The Design Process of Cooling Channel by Genetic Algorithms (GAs) Based On Evaluation Function

3.1 The Genetic Algorithm

Numerical methods for calculating the extremes of a function have been applied to engineering computations for a long time. Although these methods may perform well in many practical cases, they may fail in more complex design situations. In real design problems the number of design parameters can be very large, and their influence on the value to be optimized (the goal function) can be very complicated. The goal function may have many local extremes, but designers are interested in global extremes. Such problems cannot be resolved by classical methods (e.g. gradient methods); they only compute local extreme. In such cases, stochastic optimization techniques such as genetic algorithms may find a solution (a design) near the global optimum within reasonable time and computational costs. Genetic algorithms strongly differ in conception from other analytic and stochastic search methods, including gradient and simulated annealing methods. The difference is that while other methods process single points in the search space, GAs maintain a population of potential solutions.

GAs constitute a class of search methods especially suited for solving complex optimization problems. They transfer the notions of natural evolution to the world of computers, and imitate natural evolution. They were initially introduced by J. Holland for explaining the adaptive processes of natural systems and for creating new artificial systems that work on similar bases. In nature, new organisms adapt to their environment through evolution. Genetic algorithms evolve solutions to the given problem in a similar way. They maintain a collection of solutions, a population of individuals and perform a multidirectional search. The individuals are represented by chromosomes composed of genes. Genetic algorithms operate on the chromosomes, which represent the inheritable properties of the individuals. The fit individuals solve the optimization problem, while the weak individuals, die off. New individuals are created from one or two parents by mutation and crossover, respectively. They replace the old individuals and are usually similar to their parents. As a consequence, in a new generation there will appear individuals that resemble the fit individuals from the previous generation.

3.1.1 The Concept and Character of GA

GAs are efficient and generally applicable in global search procedures based on a stochastic approach which relies on the Darwinian survival-of-the-fittest principle [24]. GAs operate on a population of potential solutions to produce better approximations to the optimal solution through evolution. The population is a set of chromosomes and the basic GA operators are selection, crossover and mutation. At each generation, a new set of approximations is created by selecting individuals and breeding them together using crossover and mutation operators which are conceptually borrowed from natural genetics. Hopefully, this process leads to the evolution of better
individuals with near-optimum solutions over time. Generally, GA performs well in finding areas of interest even in a complex, real-world scene. While a GA may never produce the absolute best (global optimum), it is mathematically likely to get very close to it by using a fraction of the computational requirements of an exhaustive deterministic search. The advantages of GAs would include not only the global nature of the search process, but also the indifference to system specific information.

The process of evolution is directed by fitness. The evolutionary search is conducted towards better regions of the search space on the basis of the fitness measure. Each solution in a population is evaluated based on how well it solves the given problem. GAs use a separate search space and solution space. The former is the space of coded solutions, i.e., genotypes or chromosomes consisting of genes. The latter is the space of actual solutions, i.e., phenotypes. The genotype must be transformed into its corresponding phenotype before fitness is evaluated.

3.1.2 The Genetic Process

Solving a problem with GA starts with designing proper individuals, fitness evaluation and termination criterion. Many individuals are possible for a given problem, some being better than the others. The termination criterion usually allows at most some predefined number of generations and checks whether an acceptable solution has been met. The process is as follows (see Figure 3.1):

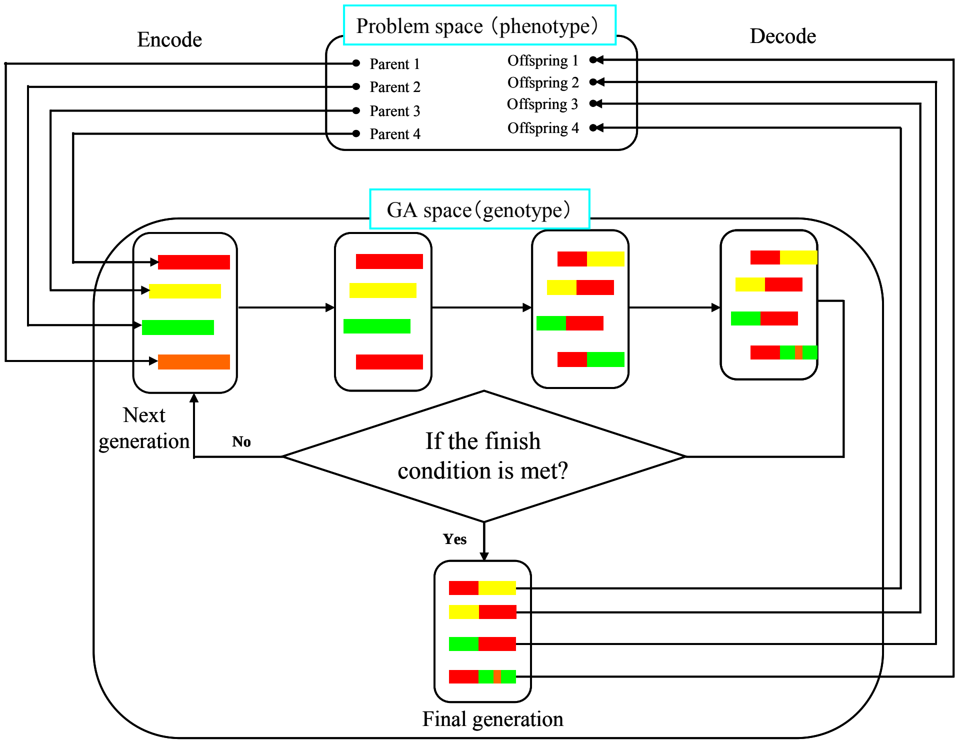


Figure 3.1 Genetic Algorithm Process

1. The initial population is filled with individuals that are generally created at random.

2. Individuals in this population are evaluated using the fitness measure.

3. From the current population, individuals are selected for reproduction, based on their fitness values. Different types of selection mechanisms can be used (e.g. fitness proportional, ranked, tournament selection).

4. New individuals (offspring) are created by applying the genetic operators to parent individuals. Reproduction copies selected individuals from the current population. Crossover combines the genetic code of two parents. Local changes are introduced into the genetic code of one individual by mutation. Different types of crossover and mutation operators can be used according to the features of the specific problem (see Figure 3.2).

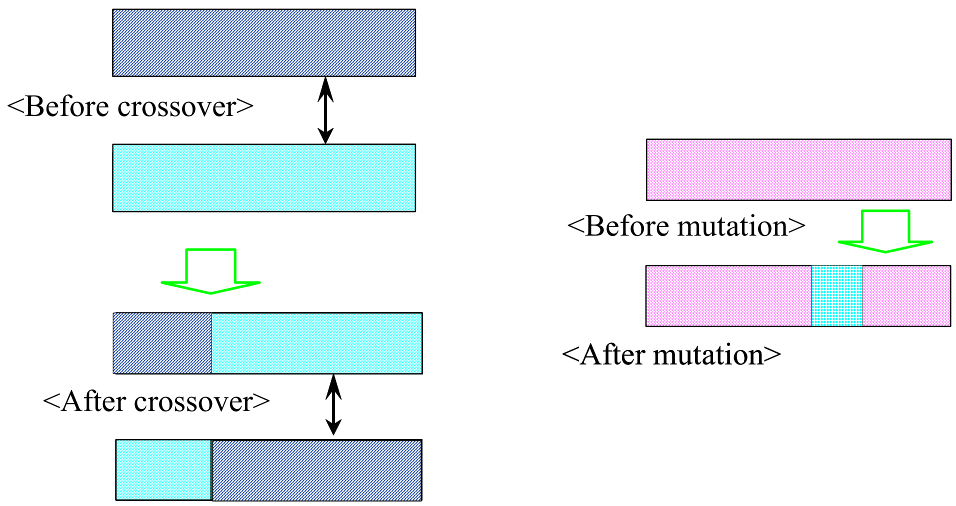


Figure 3.2 Crossover and Mutation

5. New individuals are evaluated using the fitness measure. New population is created by extending the current population with the new individuals and then omitting the least fit individuals.

6. If the termination criterion is met, the best solution is returned.

7. Steps 3 to 6 are repeated until the termination criterion is satisfied. An iteration is called one generation.

The above process can easily be transferred into an algorithm and a computer code.

3.1.3 Application of Genetic Algorithms in Design

Genetic algorithms are being applied to many areas of engineering design in mechanical engineering, electrical engineering, aerospace engineering, architecture and civil engineering, etc [36], [44]. It is practically impossible to give a comprehensive overview of all existing applications even for one such area. Instead, we discuss branches of engineering design in which GAs are extensively used [37]:

Shape optimization. The common feature of all these areas is their strong geometric nature, which is also important in most engineering design problems. This also indicates that genetic algorithms can be efficient in solving problems with very different engineering content within a similar framework by using similar procedures.

3.1.3.1 Shape Optimization

One of the most important characteristics of technical objects is their shape. Functionality and manufacture strongly depend on shape [34]. Considerable efforts are continuously exerted in engineering science to find better shapes, or to optimize the shape of a component subject to engineering constraints.

Shapes can be described by a great variety of representations; a structured set of shape parameters (scalars, vectors), or discrete representations such as pixels or voxels may be appropriate. In shape optimization, values of the shape variables result in an optimal value of a target parameter. This latter characterizes the object from a technical, economical or aesthetic aspect or combinations of these. In engineering applications, the relation between the target value and the shape variables of the fitness functions for GAs may be very complex, having many local extremes, including discontinuities. While classical methods for optimization often fail under such complicated conditions, genetic algorithms may offer solutions in many practical situations.

3.1.3.2 Cell GA

An alternative way of representing the shape of an object to be optimized is to subdivide the space into small rectangular domains (pixels in 2D, voxels in 3D), and assign them a binary full value (1) for material or empty value (0) for void (see Figure 3.3.), or integers for different materials [28], [53].

The cellular representation has the advantage that any shape can be represented with a certain accuracy, which can be increased by increasing the resolution. At the same time, the cellular representation can be mapped directly into two or three-dimensional binary genetic representations, resulting in a two or three-dimensional array chromosome. By applying this representation, domain specific knowledge and geometric constraints can easily be built into the genetic process [35].

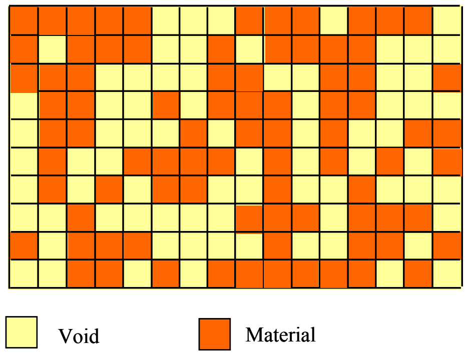


Figure 3.3 Cell Representation

3.2.1 Design Methods

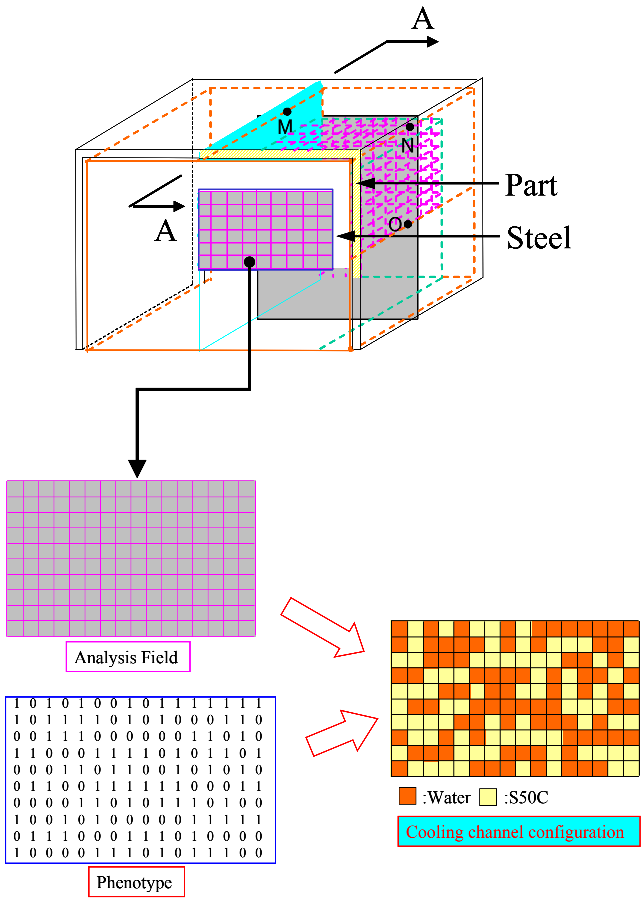


Figure 3.4 Definition of Analysis Field

The analysis field is shown in Figure 3.4. The design field is first converted into a finite mesh, with quadrilateral finite elements corresponding to each design field element [31]. All finite elements corresponding to water are given a small Young's Modulus. Elements corresponding to the material are given a large Young's Modulus. Bendse and Kikuchi suggest that if a soft material's Young's Modulus is 10^{-2} to 10^{-3} times that of a hard material, the soft material can be regarded as a void or hold [56]. A similar method is used by Jensen (14). We compare this meshing technique with an adaptive meshing technique where finite elements corresponding to void elements receive a Young's Modulus 10^{-5} times that of a material element.

3.2.2 Genotype and Phenotype Definition

We define the cooling channel shape according to the presence of cooling elements in the model field [43]. We define them as 1 if cooling elements exist in the model field, and define them as 0 if there are no cooling elements in the model field. Then, the phenotype will be transformed into genotype from up to down and from left to right.

3.2.3 Genotype and Phenotype Transfer

The basic method is depicted in Figure 3.5. Firstly, we change the genotype into phenotype i.e. Change a one-dimensional model into a two-dimensional model, simultaneously expressing the two-dimensional model with a finite element code.

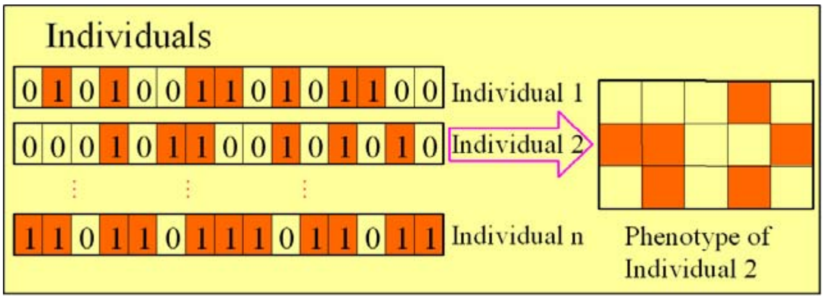


Figure 3.5 Genotype and Phenotype

3.2.4 Finite Element Analysis

For every individual, we divide analysis model with the quadrilateral element, combinative finite element into two-dimensional model [14], [51]. Then we conduct a numerical analysis using the finite element method [10] and code the element using PATRAN software. 20 individuals are generated by random function in our study as the initial population of the 1st generation.

3.2.5 Selection, Crossover and Mutation

During the selection operation, each individual in the population is arranged according to the fitness value, which is the inverse number of evaluation function. Next, several of the individuals with high values are forced to stay into the next generation as elite individuals. As for other individuals, crossover or mutation is executed, and offspring are created for the next generation. Regarding crossover, new offspring are created, with characters of the two parents partially preserved, and such individuals are expected to show higher fitness value than their parents.

When offspring for subsequent generations are created using only crossover, different individuals are increasingly hard to detect with the generation transition, and significant improvement in fitness value cannot be expected. Thus, for several percent of the gene of individual genotype, a random part of the gene is determined by random numbers using probability laws has a mutation, by this way; a treatment to automatic design shape of the cooling channel is performed.

In the present study, to every individual take two-point crossover way and crossover rate is 0.5, mutation rate is 0.1.

3.2.6 The Convergence Condition

We think that the convergence condition could be satisfied when the fitness of the best individual and all individuals do not change through 20 generations. At the same time, the calculation can be finished.

3.2.7 The Follow of Automatic Design

In the present study, we search the automatic generation shape by GA method [13]. The flow chart of automatic design is shown in Figure 3.6.

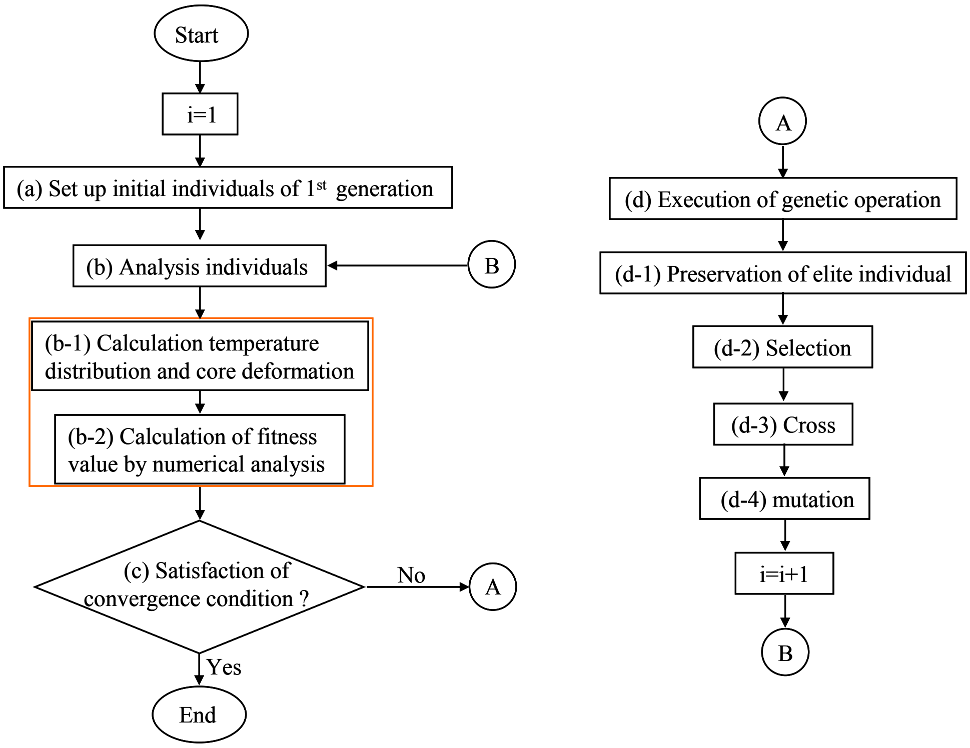


Figure 3.6 Flow Chart of Automatic Design

First, the population, consisting of several individuals expressing a cooling channel is set up and defined as the 1st generation (process a) as is shown in Figure 3.7. Next, (process b) is conducted for the individuals using two sub-processes, namely:

i) (process b-1), where the temperature distribution of product face and pressure deformation of mold surface are calculated using a temperature and deformation analysis based on non-linear finite element method and linear static deformation [11], and

ii) (process b-2), calculation of fitness value using a fitness function.

After process b, the automatic design for cooling channel is completed or conducted based on the convergence condition (process c). The convergence condition is satisfied when no fitness value can be observed regarding individuals with their maximum values over the succeeding generation.

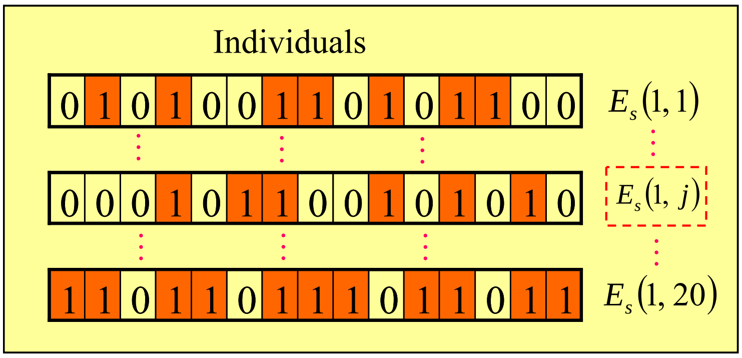


Figure 3.7 The First Generation

When the convergence condition is not fulfilled, genetic operation is executed for all individuals (process d). This process consists of four operations: preservation of elite individuals with high fitness values (process d-1), selection of individuals with low fitness values (process d-2), crossover between two individuals (process d-3), and mutation (process d-4). With each operation, new individuals are created as offspring for succeeding generation. Then, the process b is repeated and the above mentioned series of processes repeat until the convergence condition is fulfilled.

3.2.8 Constraint Handling

When a genotype, operated by using crossover and mutation, is decoded to the phenotype, there are some cases in which the finite element model is not suitable for the geometry of the mold. Since these types of mold are difficult to manufacture, it is necessary to have the shape modified from the Automatic generation result [42],[49],[50]. The domain of shape optimization is regarded as a black-and-white digital image. Each element is analogously considered as one pixel and its color is represented by the binary number, where white is steel material and red is water. Similar image-processing-based handling approach for continuous structural topology optimization has been proposed by Sigmund (18) to eliminate mesh dependency and checkerboard problems.

In image processing [23], either a four-neighborhood connectivity, where only vertical and horizontal directions can be followed, or an eight-neighborhood connectivity, where horizontal, vertical and diagonal directions are allowed, can be used, as shown in Figure 3.8. To determine the design connectivity more effectively, the four-neighborhood connectivity is employed. In this study, connected component labeling, which labels each region with a unique (integer) number, is used for region identification. With this labeling, the number of connected regions and their relative areas can be readily obtained with a simple inspection of the labeled image's histogram. A recessive gene technique is taken to deal with the connected component [42], defined by some variables in this study. The process of shape modification is shown in Figure 3.9.

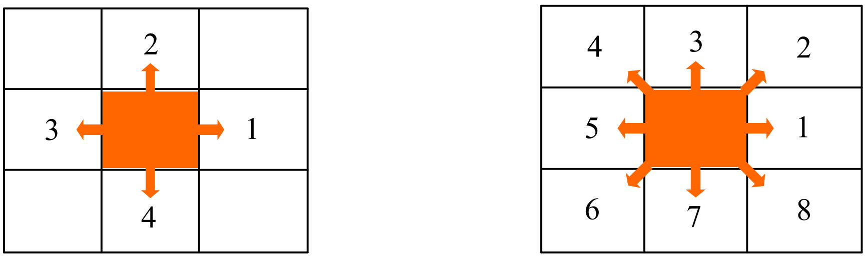
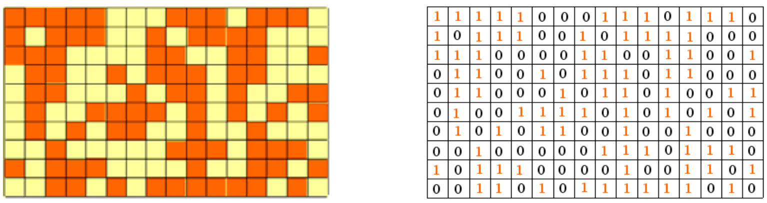
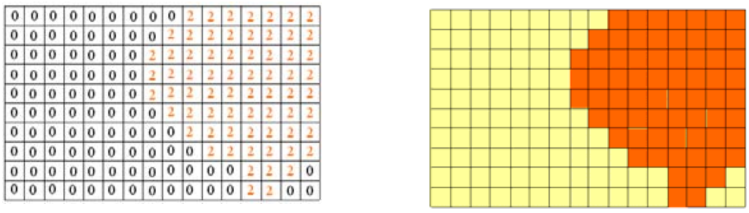


Figure 3.8(a) Four Neighborhood   Figure 3.8(b) Eight Neighborhood

Figure 3.8 Image Processing Based Connectivity



(a) Original Shape   (b) Bit Array Representation



(c) Connected Labeling   (d) Modification Shape

Figure 3.9 Process of Shape Modification

3.2.9 The Convergence Condition

Generally, the GA generation process continues until a convergence condition is satisfied. In our study, the convergence conditions were considered to be satisfied when the fitness of the best individual and all individuals do not change through 20 generations. At that point, the calculation was considered finished.

3.2.10 The Flow of Automatic Design

In the present study, we automatically searched for the cooling channel shape by the genetic algorithm method, and a flow chart of the automatic design is shown in Figure 3.10.

First, a population consisting of 20 individuals expressing a cooling channel was set up and defined as the 1st generation (process a). Then, shape modification was performed (process b). The following two processes were conducted for individuals (process c): calculation of the temperature distribution of product surface and pressure deformation of the mold surface, and calculation of the fitness value using a fitness function. After process b was complete, automatic design for cooling channel was performed based on whether the convergence condition had been met (process d). The convergence condition is met when no fitness value could be observed regarding individuals with their maximum values over the succeeding generation.

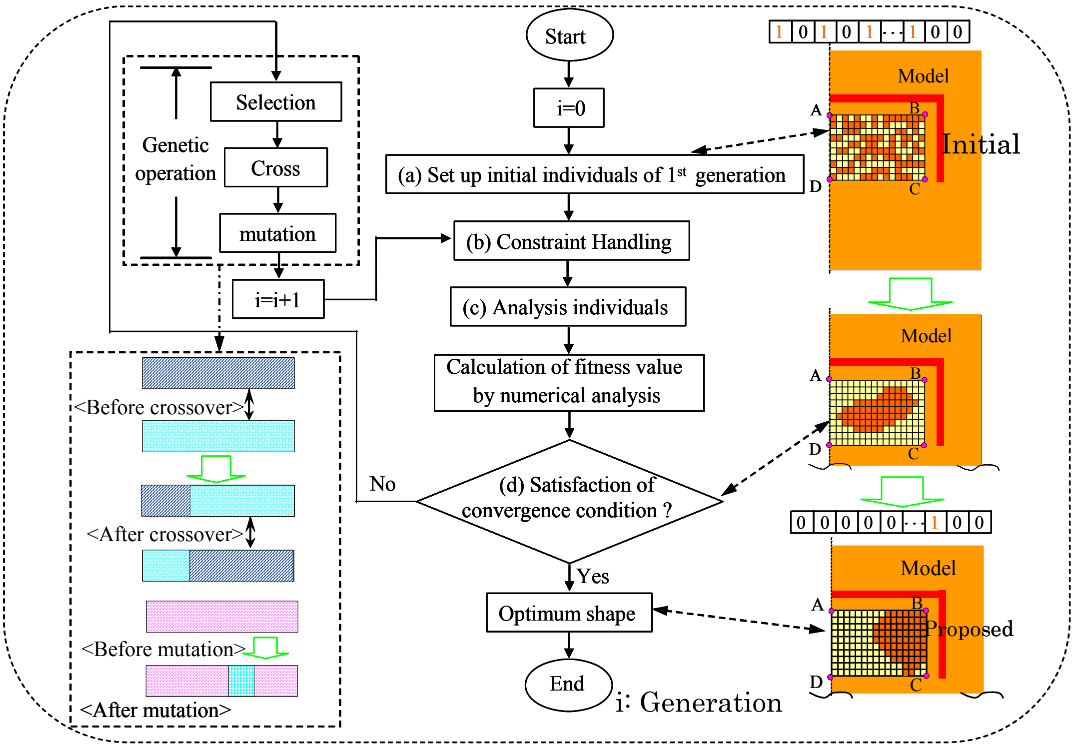


Figure 3.10 Flow Chart of Automatic Design

When the convergence condition is not fulfilled, genetic operation is executed for all individuals. This process consists of four operations: preservation of elite individuals with high fitness values, selection of individuals with low fitness values, crossover between two individuals, and mutation. With each operation, new individuals are created as offspring for the succeeding generation. Then, process b is conducted again, and the above-mentioned series of processes is repeated until the convergence condition is fulfilled.

3.3 Evaluation Function

3.3.1 Temperature Evaluation Function

Firstly, several items used for the evaluation are considered as follows [26], [32], [33], [40].

Evaluation curve line: the curve line used for the evaluation of cooling uniformity in a three-dimensional model, which is in the product surface and contacts with the mold cavity. It can be taken for the entire product line or a part of it [3],[8].

Evaluation Point: an arbitrary point on the evaluation surface used to calculate the temperature error on this point [12]. Temperature error is the temperature difference between an evaluation point and the average value of the evaluation surface. By using these concepts in the design for minimizing the combination of the uniformity of the product surface temperature distribution and the cooling time related to productivity [48], the objective function is calculated as follows:

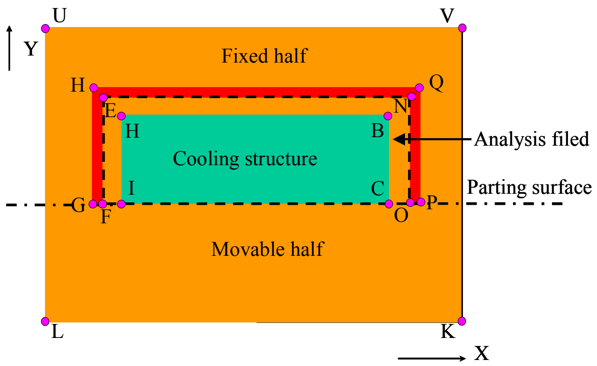


Figure 3.11 (a) Analysis Model

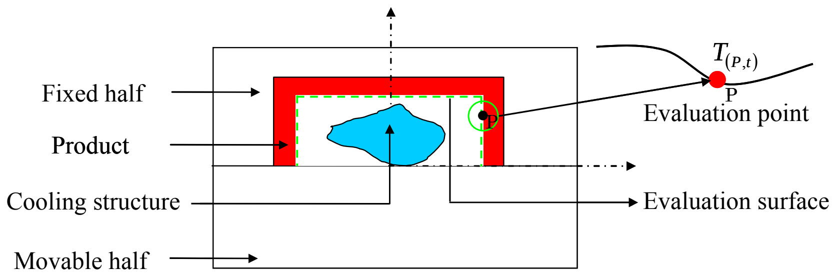


Figure 3.11 (b) Evaluation of Temperatures

Figure 3.11 Temperature Evaluation Model

Firstly, calculate the average temperature of all points and the temperature error of the evaluation point P at the moment on the evaluation surface. They are defined by Equation (3.3), (3.4).

$$P = (x(q,r),\ y(q,r)) \qquad (P \in \Omega,\ 0 \le q \le 1,\ 0 \le r \le 1) \tag{3.1}$$

$$S = \iint_{\Omega} dqdr \tag{3.2}$$

$$T_{ave}(t) = \frac{1}{S}\iint_{\Omega} T(P(q,r),t)dqdr \tag{3.3}$$

$$\Delta T(P,t) = T(P,t) - T_{ave}(t) \tag{3.4}$$

where, $\Delta T(P,t)$ is the temperature of evaluation point P at this moment. $T_{ave}(t)$ denotes the average temperature of the all points on the evaluation surface.

Next, use Equation (5) to calculate the dispersion of temperature distribution on the evaluation surface in the whole cooling process.

$$f_{t_c}(P) = \frac{1}{t_c}\int_0^{t_c} \Delta T^2(P,t)dt \quad (3.5)$$

Finally, for all points in the whole cooling process, small values and even distribution of $F(s)$ are expected. This can be calculated by Equation (3.6).

$$F_s(i,\ j) = \frac{1}{S}\iint_\Omega f_{t_c}(P)dqdr \quad (i \in generation\ ,\ j \in individual\ ) \quad (3.6)$$

Equation (6) gives a total description of mold cooling, which considers both the spatial factors and the temporal factors in the whole cooling process. This value can describe the cooling uniformity. A small value means a good temperature distribution on the evaluating product surface.

3.3.2 Deformation Evaluation Function

The injection process is divided into four main stages: cavity filling, cavity packing, product cooling and product ejected stages. The molten resin is injected at high flow rate into the cavity, usually through a gate [52]. Immediately after the filling, high hold pressures are set during the packing phase to generate a post-filling, which compensates the shrinkage of polymer due to its cooling [25], [27], [46]. The polymer pressure in mold cavity often reaches several tons. Under such pressure levels, it leads to a cavity deformation due to mold and machine compliance. Consequently, injection molding will cause variations in cavity dimension, and further reduce the precision of molding. During a deformation evaluation, several items will be considered as follows.

Evaluation curve surface: the surface used for the evaluation of deformation change in a three-dimensional model, which is in the mold surface and contacts with the product. It can be taken as the entire mold line or a part of it.

Evaluation Point: an arbitrary point on the evaluation surface used for the calculation of deformation error on this point.

Deformation error: the displacement difference between an evaluation point and the average value of the evaluation surface. By applying these concepts in the design for minimizing the deformation of the mold,

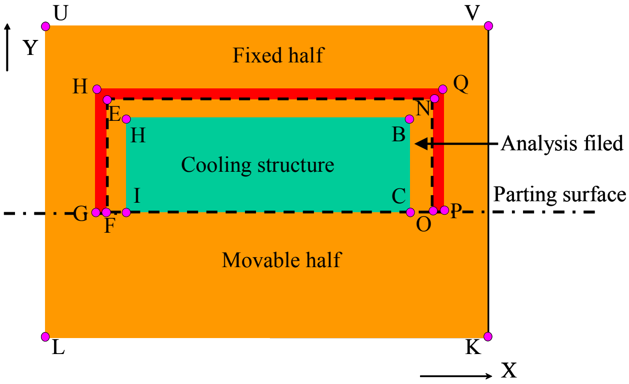


Figure 3.12 (a) Analysis Model

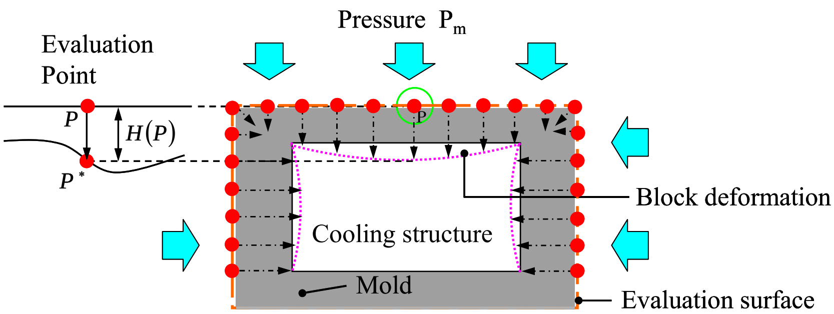


Figure 3.12 (b) Evaluation of Deformations

Figure 3.12 Deformation Evaluation Model

Firstly, calculate the average deformation of all points and the deformation error of evaluation point P infinitesimal deformation at movement direction. They are defined by Equation (3.7),(3.8).

$$H_{ave} = \frac{1}{S}\iint_{\Omega} H\left(P\left(q, r\right)\right)dqdr \tag{3.7}$$

$$\Delta H\left(P\right) = H\left(P\right) - H_{ave} \tag{3.8}$$

where, $H(P)$ is the deformation of evaluation point P at movement direction, H_{ave} denotes the average deformation.

Next, for all points in the whole evaluation surface, small values are expected. This can be calculated by Equation (3.7).

$$N_s(i,\ j) = \frac{1}{S}\iint_{\Omega} \Delta H^2(P)\,dqdr \quad (i \in generation\ ,\ j \in individual\ ) \quad (3.9)$$

Equation (9) gives a total description of mold deformation, which can describe the deformation uniformity. A small value means a good deformation on the evaluating mold surface.

3.3.3 Automatic Design

When minimizing the objective function, the temperature analysis and the deformation analysis are essentially required for an optimization design. Among them, the temperature analysis and the corresponding deformation analysis are achieved in section 3.3.1 and section 3.3.2, respectively. For minimizing the combination of the uniformity of the product surface temperature distribution and the mold surface deformation related to pressure, the normalized objective function is chosen as:

$$E(generation) = \left\{ \alpha \frac{F_s(i,\ j)}{\tilde{F}_s(1,\ j_A)} + (1-\alpha)\frac{N_s(i,\ j)}{\tilde{N}_s(1,\ j_A)} \right\} \quad (3.10)$$

$$\tilde{F}_s(1, j_A) = \frac{1}{n}\sum_{j=1}^{n} F_s(1,\ j)$$

$$\tilde{N}_s(1, j_A) = \frac{1}{n}\sum_{j=1}^{n} N_s(1,\ j)$$

$$(i \in generation\ ,\ j \in individual\ )$$

where, $\tilde{F}_s(1, j_A)$ is the reference value for the product surface temperature distribution, which is the first individual of the $F_s(i,\ j)$ for a temperature evaluation. $\tilde{N}_s(1, j_A)$ is the reference value for the mold surface deformation, which is the first individual of $N_s(i,\ j)$ for a deformation evaluation, and α is the weighting parameter. There is a different evaluation rule for temperature evaluation and deformation evaluation, so we have to take reference evaluation to normalized objective function.

Chapter 4

4.0 Case Studies via Numerical Analysis

This chapter provides case studies via numerical analysis to show how to design the cooling channel in plastic injection mold. In particular, the automatic design procedure of cooling channel is discussed through the case studies [47].

4.1 Purpose of Numerical Analysis

This chapter is applications of the evaluation function and design procedures proposed in chapter 3. The main contents are summarized as follows.

1. Show how to apply the proposed methods and procedures on cooling channels design in injection molds through numerical analysis

2. Base on the evaluation result; confirm how to make a proper design from initial cooling channels in an injection mold.

3. Confirm the utility by applying the proposed method to automatic design cooling channels. Also confirm the utility of the proposed methods applied to complicated shape numerical analysis.

4.2 Analysis Example

4.2.1 Analysis Model

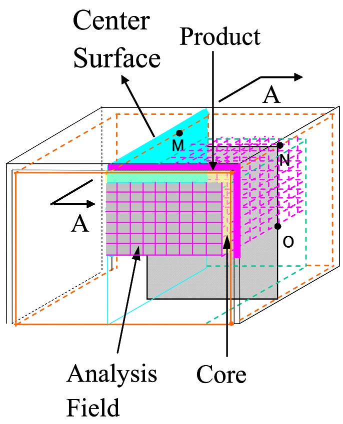


Figure 4.1 (a): 3-D Model

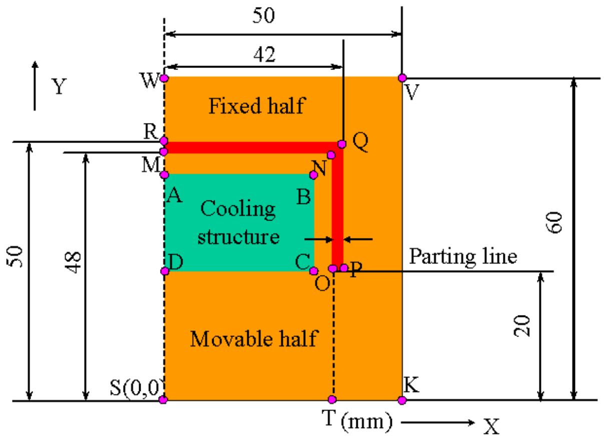


Figure 4.1 (b): 2-D Model

Figure 4.1: Analysis Model

Figure 4.1 shows the model used for numerical analysis. Figure 4.1 (a) is the 3-D box-shape product and the mold which is used for forming the product. In order to simplify the simulation, surface ABCD is chosen as the analysis section which is a 2-D model shown in Figure 4.1 (b). Because the model is symmetrical, this analysis takes the right side as the analysis object. The product in this model is the shape of a box with 2-mm walls. Because the resin product has a sharp corner N, in the inner side of the product, especially around this corner, the condition of heat diffusing is poor, so it is easy to become a heat spot in this region.

The rectangular field ABCD was divided into 16 × 10 elements. Thereby, a genotype of which the length is 160 can be achieved. There are 20 individuals for each generation in our study. The boundary conditions of the numerical analysis model that was used to calculate the temperature distribution of the product and the pressure deformation of mold are shown in Figure 4.1. Because the product and mold are symmetrical to the line WS, line WS can be considered an insulated surface in terms of the heat equilibrium. Water, SKD11 and PS are the cooling material, mold material and resin material in this study, respectively.

4.2.2 Analysis Conditions and Assumptions

The concrete method used for the analysis is FEM (Finite Element Method), the time interval during the calculation is setting at 0.05sec. The target resin is assumed as PS, and the filling temperature is set at 240℃. Molding conditions and properties used in the numeral analysis are shown in Table 4.1.

Table 4.1: Molding Conditions and Properties

Resin (PS)	Thermal conductivity (W/m・K) Specific heat (J/kg・K) Density (Kg/m^3) Filling temperature (℃)	0.15 1340 893 240
Mold (SKD11)	Thermal conductivity (W/m・K) Specific heat (J/kg・K) Density (Kg/m^3) Temperature (℃)	29.3 460 7850 40
Coolant (Water)	Thermal conductivity (W/m・K) Specific heat (J/kg・K) Density (Kg/m^3) Temperature (℃)	0.6 4180 1000 25
Core Block (SKD11)	Injection Pressure (MPa) Elastic Modulus Density (Kg/m^3) Poisson Ratio	5.8 2.1E+011 7800 0.3

For the evaluation of cooling uniformity, the evaluation curve is chosen as the range of resin surface MNO, this means the entire surface takes the same importance to join the evaluation.

After the filling stage is finished, the temperature of the resin drops, when the highest temperature inside the resin area reaches to 105℃, which is the solidification temperature of the PS resin, the solidification of the resin is regard as a finish state.

There are some differences between the simulation and the practical mold process. (a) There is a 1~2 degree temperature difference between the coolant at the inlet and outlet. This temperature is usually controlled in the practical mold process. (b) The temperature of resin changes during the filling process. (c) There is a complicated contact state between the mold and the resin. (d) There is heat transfer between mold and air. In order to simplify the process of analysis, there are several assumptions in this analysis listed as the following:

a) The initial temperature of resin injected to mold cavity is assumed to be uniform. This assumption is according to that the filling stage is finished in a very short time. If the product is not in a small volume, it can be considered that the solidification of resin begins after the completion of resin filling.

b) No heat generates during the solidification of resin. And, the thermal properties of the resin, mold material, and coolant are assumed to be constant.

c) The molten resin and the cavity wall are assumed to be in perfect thermal contact.

d) The temperature of the coolant, surrounding air and contact surfaces between the mold and the platens of injection machine are assumed to be in steady states.

f) The packing pressure or the holding pressure does not influence the solidification of resin.

4.3 Result Analysis

This section discuss how to realize an optimum design of cooling channel by minimize the evaluation value. The procedure has been given in section 3.3 of chapter3. By following the procedure, from random initial shapes of cooling channels in mold, automatic generation is executed to reach the optimum state of shape, size and position.

The analysis model is shown in Figure 4.1. A 2-D unsteady numerical analysis has been made to perform the evaluation and find the temperature distribution on the product surface. The cooling time was set to 20 seconds. The inner surface MNO of the product was chosen as the evaluation range of the product cooling and mold deformation. Analysis software used in the present study is NASTRAN 2005 [5]. There were 20 individuals in each generation in our numerical experiments, and the optimization lasted 100 generations. We had 10 different calculations with different initial conditions. The resulting initial shape channel is shown in Figure 4.2. The optimization cooling channel shape is shown in Figure 4.3. The fitness transition of each analysis step is shown in Figure 4.4. After the 73rd generation, no change in the fitness of the best individual and all individuals were seen. After that, through the 20 generations, since no change in fitness for individual with the least fitness was seen, the treatment was halted at the 100th generation. It took 60 hours to finish the calculation, and the smallest value was 0.8908. Automatic generation produce from initial shape is shown in Figure 4.5.

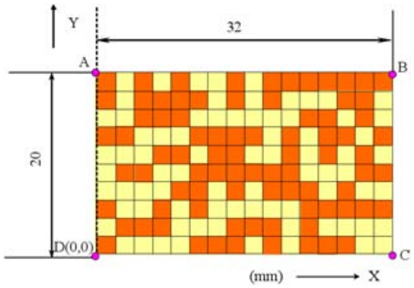


Figure 4.2: Initial Shape of the Cooling Channel

Water SKD11

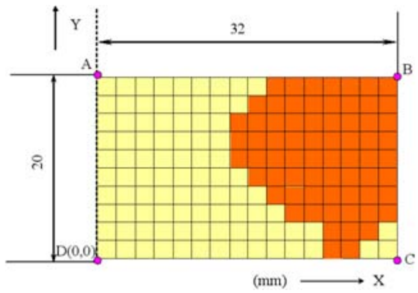
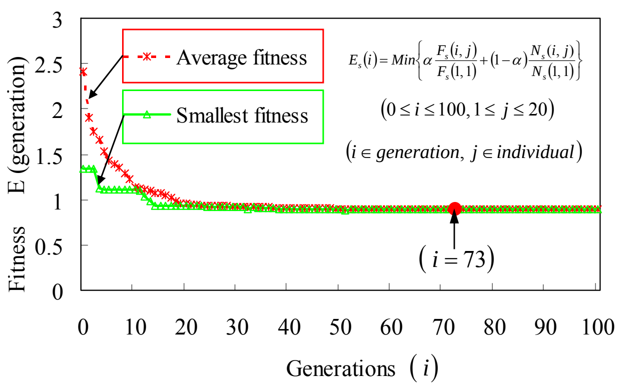


Figure 4.3: Final Shape of the Cooling Channel

Water; SKD11



$$Average : E_A(i) = \frac{1}{20}\sum_{j=1}^{20}\left\{\alpha\frac{F_s(i,j)}{F_s(1,1)} + (1-\alpha)\frac{N_s(i,j)}{N_s(1,1)}\right\}$$

$$Smallest : E_s(i) = Min\left\{\alpha\frac{F_s(i,j)}{F_s(1,1)} + (1-\alpha)\frac{N_s(i,j)}{N_s(1,1)}\right\}$$

$$(1 \le j \le 20)$$

$$(i \in generation, j \in individual)$$

Figure 4.4: Fitness Transition

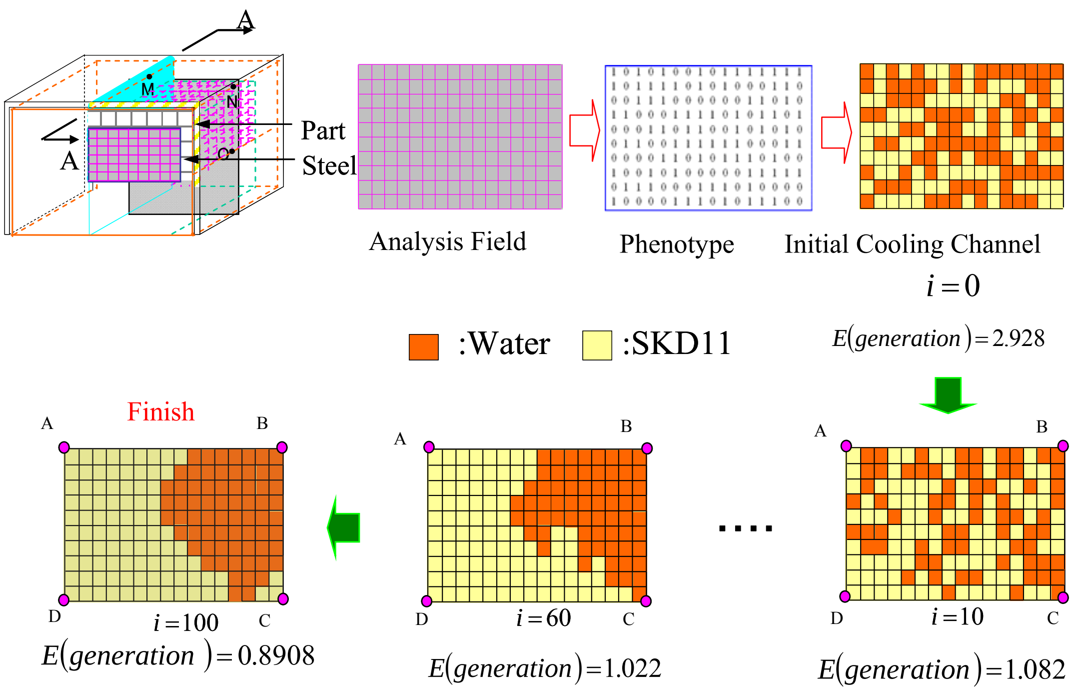


Figure 4.5: Automatic Generation Process of Cooling Channel

We compared cooling channels with and without design optimization in temperature and deformation so as to verify the effectiveness of proposed method. Two cooling channels without optimization, case_1 and case_2, are shown in Figure 4.6.

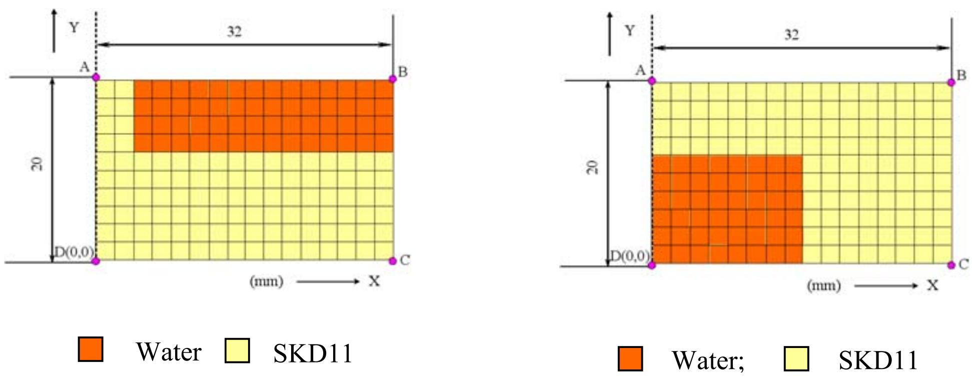


Figure 4.6 (a) Case_1

Figure 4.6 (b) Case_2

Figure 4.6: Cooling Channel Shapes of Case_1 and Case_2

We compared the temperature distribution on the evaluation curve in the cases of the initial cooling channel and the optimized cooling channel. Figure 4.7 and Figure 4.8 show the temperature distribution on the product surface MNO, taken at the time of 0, 1.5, 4.5, 7.5, 10.5 and 20 seconds after the beginning of the cooling. The vertical ordinate in the graph is the temperature; the horizontal ordinate is the expanding length of mold surface around the evaluated curve MNO.

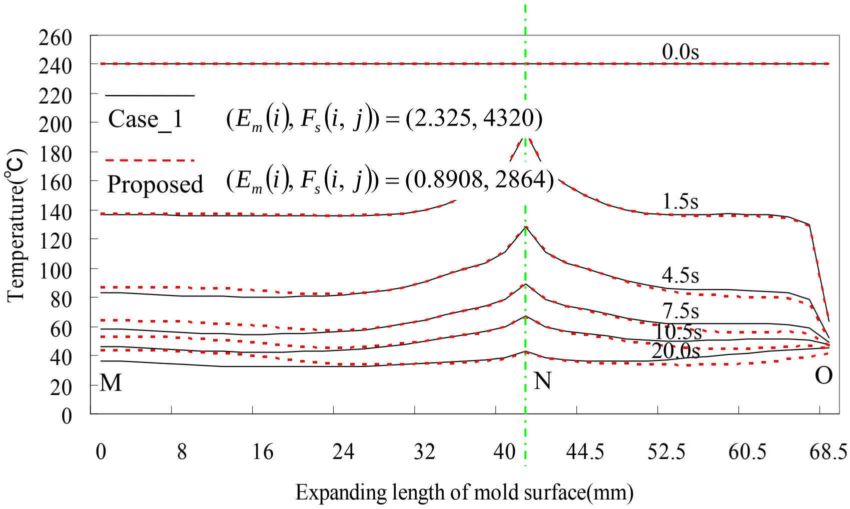


Figure 4.7: Temperature Distributions on Product Surface of Case_1 and Final

In the graph, the solid curves stand for the cooling channel without design optimization. The dashed interval curves stand for the optimized cooling channel.

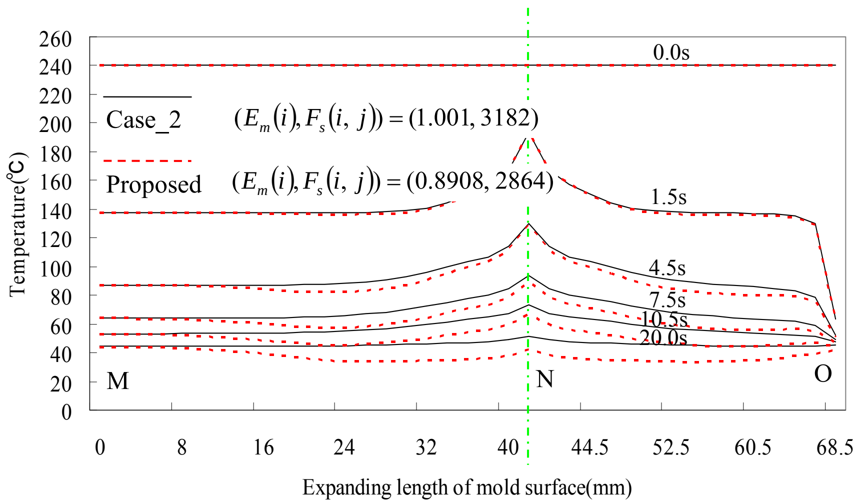


Figure 4.8: Temperature Distributions on Product Surface of Case_2 and Final

The temperature of the corner point N decreased to 43.27℃ (see Figure 4.7) at 20 seconds after the beginning of the cooling in case_1. The temperature of the corner point N decreased to 42.66℃ when cooling finished for the optimized cooling channel. There was a 0.61℃ difference between case_1 and the optimized cooling channel sample at corner point N. The temperature of the corner point N decreased to 51.75℃ (see Figure 4.8) at 20 seconds after the beginning of the cooling in case_2. There was a 9.09℃ difference between case_2 and the optimized cooling channel sample at corner point N. From these results, the optimized cooling channel lowers the product surface temperature compared with that of case_1 and case_2 as the cooling time increases.

According the graph, the following results can be confirmed.

1. In both cases, at the moment when just after the finish the filling of resin (at 0.0s, the right beginning of the cooling of resin), the temperature distribution curves are flat lines. As the heat being removed, uneven temperatures distribution appears. Especially around corner points N, the variations of temperature become sharp, and generate the peaks during the resin cooling.

2. For the evaluation values, the case with optimization shape, is smaller than the one that without optimization shape, this result verified that the evaluation function defined in equation 3.3, is corresponding with resin cooling uniformity.

The thermal deformation is one of the major problems that affect a product's quality in plastic injection molding. Once product deformation is controlled to the lowest level, production should benefit high quality products with a minimum material wastage. The product can be ejected without any significant deformation when the temperature reaches the solidifying point (glass transition temperature), the state of resin is becoming a solid. In this study, the object temperature is that the highest temperature inside the resin area decreases to 105℃, which the resin can complete its solidification under the assigned molding conditions. The temperature of the corner point N decreased to 58.26℃ (see Figure 4.9) at 20 seconds after the beginning of the cooling for the optimized cooling channel. From these results, the optimized cooling channel can meet the object temperature which has been set up.

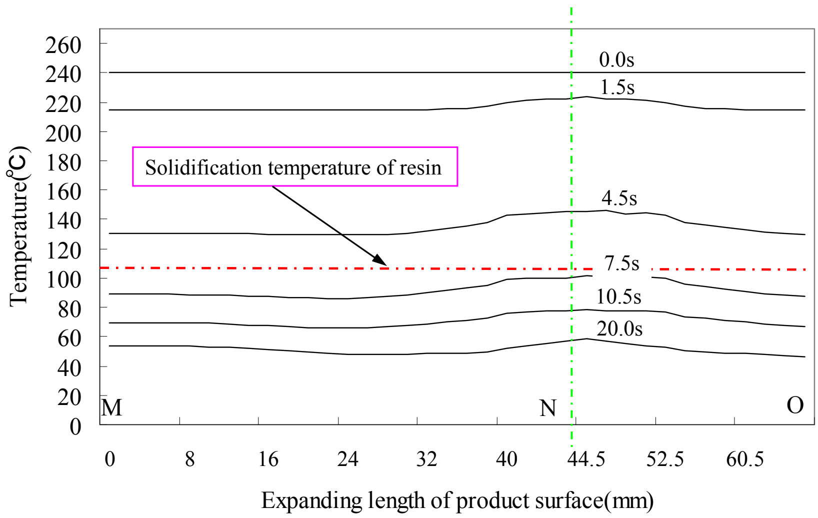


Figure 4.9: The Highest Temperature Distribution on Product Inner Surface

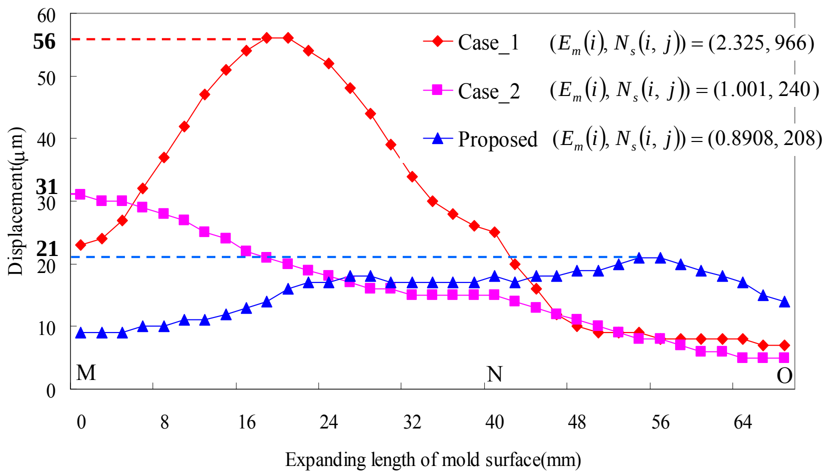


Figure 4.10: Comparison of the Deformation in Cases_1 and 2
and the Proposed Optimization Method

We compared the deformation distribution on the evaluation curve for the proposed cooling channel and cases_1 and 2. Figure 4.10 shows the deformation distribution on the mold surface MNO. The vertical ordinate in the graph is the deformation; the horizontal ordinate is the expanding length of mold surface around the evaluated curve MNO. According to this result, the maximum mold surface deformation with the optimized cooling channel is 21μm whereas the maximum mold surface deformation of the case_1 is 56μm, and that of case_2 is 31μm. The proposed optimization of the cooling channel can decrease the deformation of the mold surface.

We compared the temperature distribution over cavity surface in the cases of the pipe cooling channel (see Figure 4.11) and the optimized cooling channel (see Figure 4.12). Figure 4.13 shows the temperature distribution on the cavity surface ABC. From these results, the optimized cooling channel lowers the cavity surface temperature compared with that of pipe cooling channel.

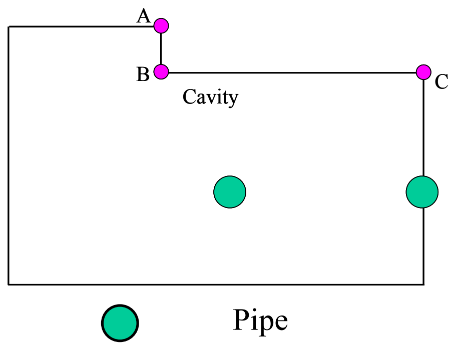


Figure 4.11: Pipe Shape of Cooling Channel

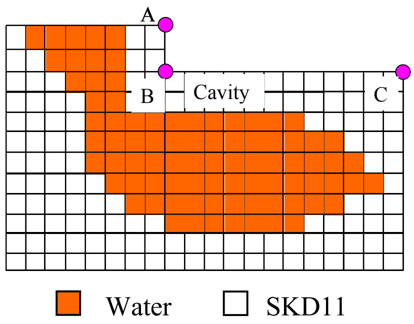


Figure 4.12: Final Shape of Cooling Channel

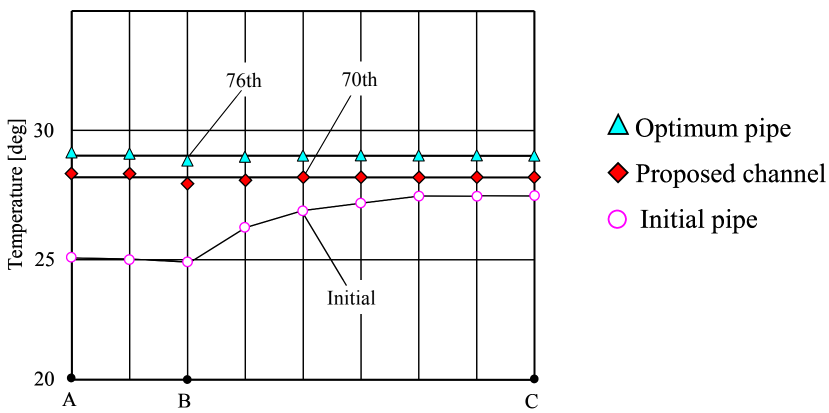


Figure 4.13: Temperature Distributions over Cavity Surface of Pipe and Final

4.4 Complicated Shape

In order to confirm the effective of the method, we have had a cooling channel optimization design of mold with complicated shape. The 3-D model of the complicated shape, initial cooling channel shape, proposed cooling channel shape were shown in Figure 4.14, Figure 4.15 and

Figure 4.16, respectively. 3-D model of proposed the cooling channel shape is shown in Figure 4.17 so as to have an intuitive sight to optimization result.

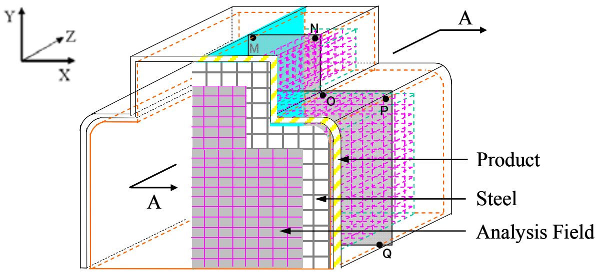


Figure 4.14 (a): 3-D Model of Complicated Shape

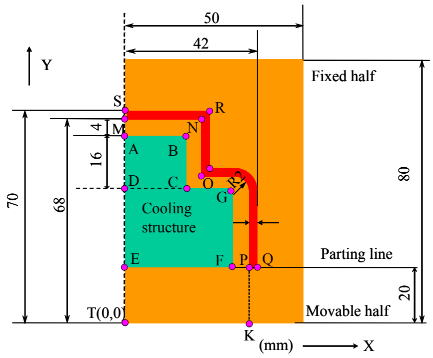


Figure 4.14 (b): 2-D Model of Complicated Shape

Figure 4.14: Analysis Model of Complicated Shape

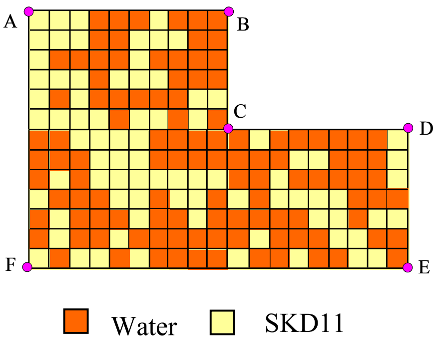


Figure 4.15: Initial Cooling Channel Shape

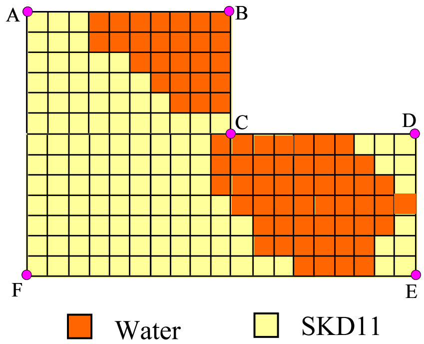


Figure 4.16: Cooling Channel Shape After Optimization

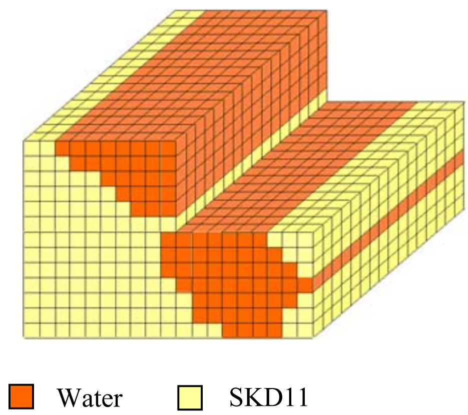


Figure 4.17: 3-D Model after Optimization

There is a comparison of the temperature distribution on the evaluation curve in the cases of initial cooling channel and the proposed cooling channel. Figure 4.18 shows the temperature distribution on the product surface MNOPQ of them, which are taken at the time of 0, 1.5, 4.5, 7.5, 10.5 and 20 seconds after the beginning of the cooling. The vertical ordinate in the graph is the temperature; the horizontal ordinate is the distance that the expanding length surrounding the evaluation curve MNOPQ.

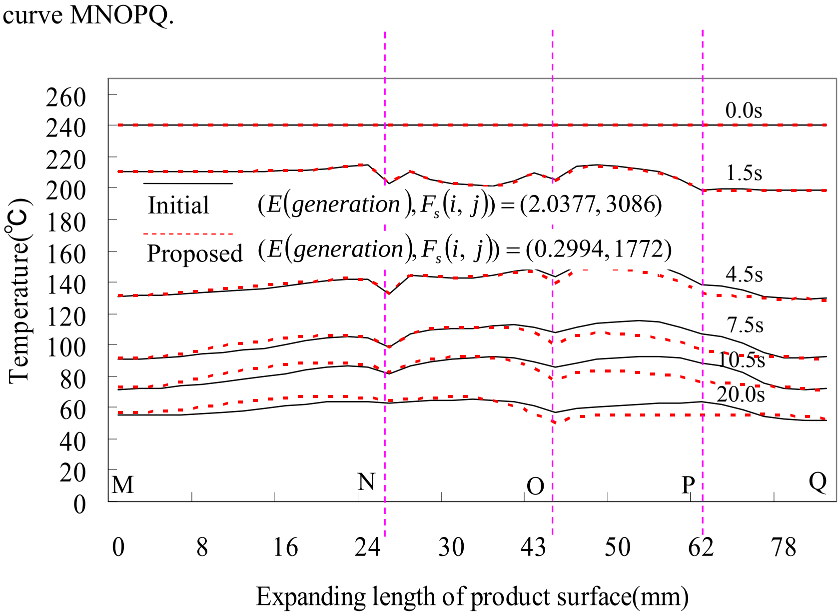


Figure 4.18: Temperature Distributions on Product Surface

In the graph, the solid curve stands for the initial cooling channel. The dashed interval curve stands for the proposed cooling channel. The temperature of the corner point O decrease to 57.13℃ when cooling finished for the initial cooling channel. The temperature of the corner point O decrease to 50.19℃ when cooling finished for the proposed cooling channel. There is a 6.94℃ decrease for the initial cooling channel and proposed cooling channel at corner point O. From this result, the proposed cooling channel can decrease the product surface temperature compared with initial cooling channel case when the cooling time increased.

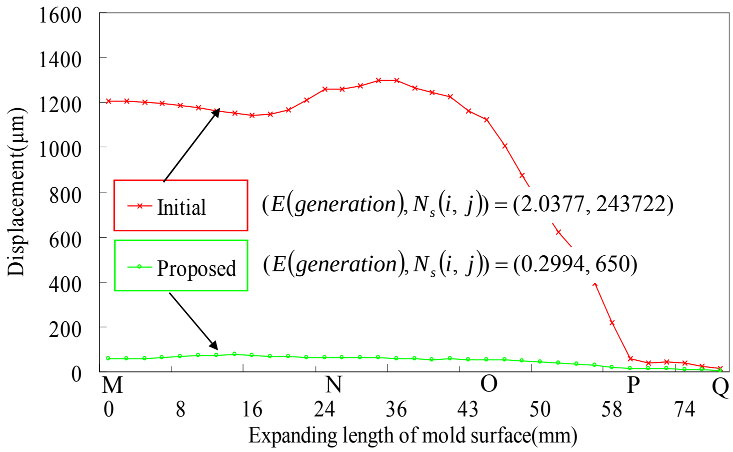


Figure 4.19: Deformation Distributions on Block Surface

There is a comparison of the deformation distribution on the evaluation curve in the cases of initial cooling channel and the proposed cooling channel. Figure 4.19 shows the deformation distribution on mold surface MNOPQ of them. The vertical ordinate in the graph is the deformation; the horizontal ordinate is the distance that the expanding length surrounding the evaluation curve MNOPQ. In the graph, the red curve stands for the initial cooling channel. The green curve stands for the proposed cooling channel. According to this result, the maximum deformation of mold surface is 1300μm for initial cooling channel, and the maximum deformation of mold surface is 76μm for proposed cooling channel. The proposed cooling channel can considerably decrease the mold surface deformation compared with initial cooling channel case.

4.5 Summary

In this chapter, by applying the propose methods and procedures on cooling channels automatic generation to numerical analysis, the evaluation of the give cooling channel is demonstrated.

Base on the result value of evaluation function, the method of making a proper design from initial given cooling channels is demonstrated.

The utility of the procedure of automatic generation for cooling channel is confirmed by the numerical analysis.

Through constructed cooling channel optimization, the convergence performance of the proposed method is confirmed.

The case of automatic generation from initial shape is confirmed. For simulation results, the optimum size and shape of cooling channels can obtain the minimum evaluation value, and most even temperature distribution on product surface.

CHAPTER 5

5.0 Sprue Bush Cooling Channel Design by using Proposed Method

5.1 Sprue Bush

The molten plastic injected from the injector nozzle will go through a bush (sprue bush), a runner, and a gate and fill up in the cavity. As the temperature of molten plastic is lowered while going through the bush and runner, the viscosity will rise; therefore, the viscosity is lowered by shear heat generated when going through the gate to fill the cavity.

So learn sprue bush design is important, because sprue bush is part that contact first time with melted plastic, bad design of sprue bush can make plastic product broken, especially sprue broken and runner broken.

Mold basic construction with sprue bush and practical sprue bush are shown in Figure 5.1 and Figure 5.2, respectively.

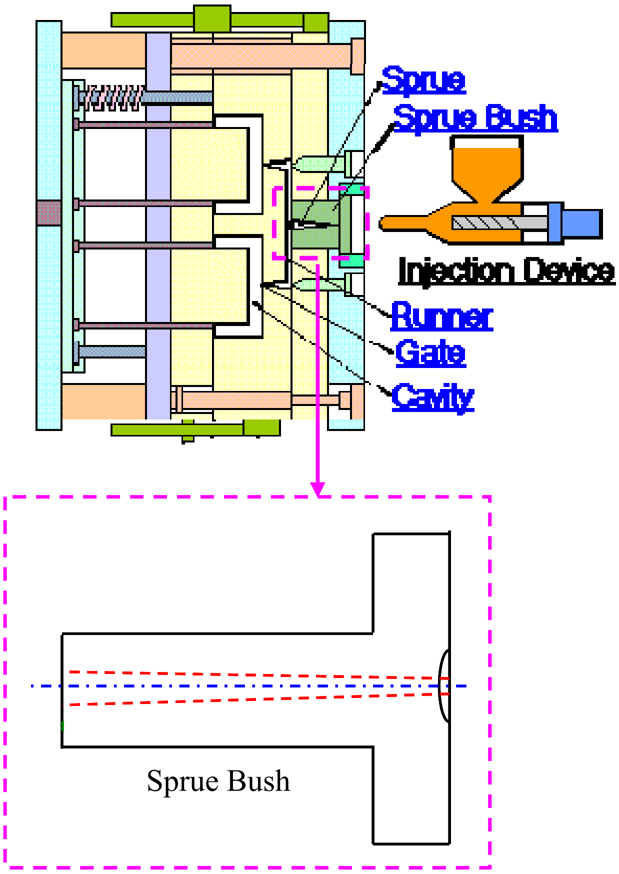


Figure 5.1: Mold Basic Construction With Sprue Bush

Figure 5.2: Practical Sprue Bush

5.2 Research Statement

In the plastic injection molding, the cooling process takes the longest time in one molding cycle. A sprue bush is one of the parts that need long time to solidify because of its thickness. In general, it can be cooled by cooling channel in mold plates. But, its efficiency of heat exchange of the sprue part may be low, because these channels are used to cool product parts mainly. Sprue Bush with cooling channel has a cooling channel inside itself, so it can cool a sprue bush part directly. Therefore, it contributes to improving production performance of molding.

In the plastic injection molding, the temperature of molding die has the greatest influence on product qualities, so it should be controlled to the temperature fluctuations among seasons and between day and night. Sprue bush with cooling channel can produce products with stable quality, because it can adjust the temperature of sprue part that is hard to control. Cooling channels studies of sprue bush are as follows:

5.2.1 Sprue Bush with Circle Cooling Channel

Cooling channel of an sprue bush is crucial to the performance of the product, influencing both the rate of the process and the resulting quality of the product. However, generally cooling channel designs and manufacture have been confined to relatively simple configurations, primarily due to limitations of the manufacturing methods and the lack of a design methodology appropriate for cooling channels. General cooling channel sprue bush is a straight-line cooling channel combination as shown in Figure 5.3. This way is difficult to effect cooling the product in sprue bush, further effect the productivity.

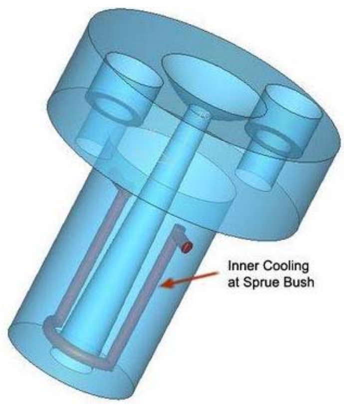


Figure 5.3: Sprue Bush with Circle Cooling Channel

5.2.2 Sprue bush with slit cooling channel

Uneven cooling of a process in a sprue bush will generate various molding defects. In order to solve these problems, the slit cooling channel in the molding is proposed. The mold with curve cooling pipe can be manufacture using Selective laser sintering (SLS) method. The 3 D sprue bush with slit cooling channel and structure configure of sprue bush with cooling channel are shown in Figure 5.4 and Figure 5.5, respectively.

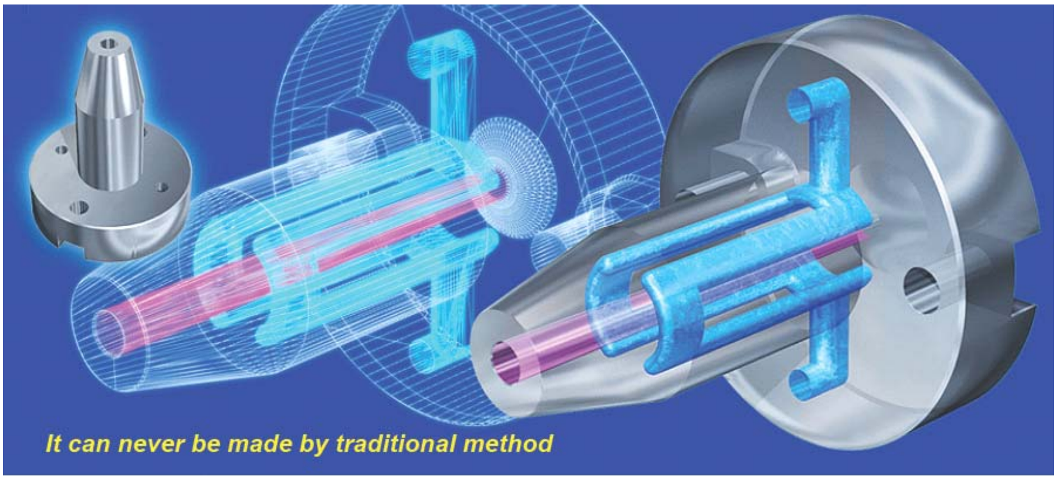


Figure 5.4: 3 D Sprue Bush with Slit Cooling Channel (www.opmlab.net)

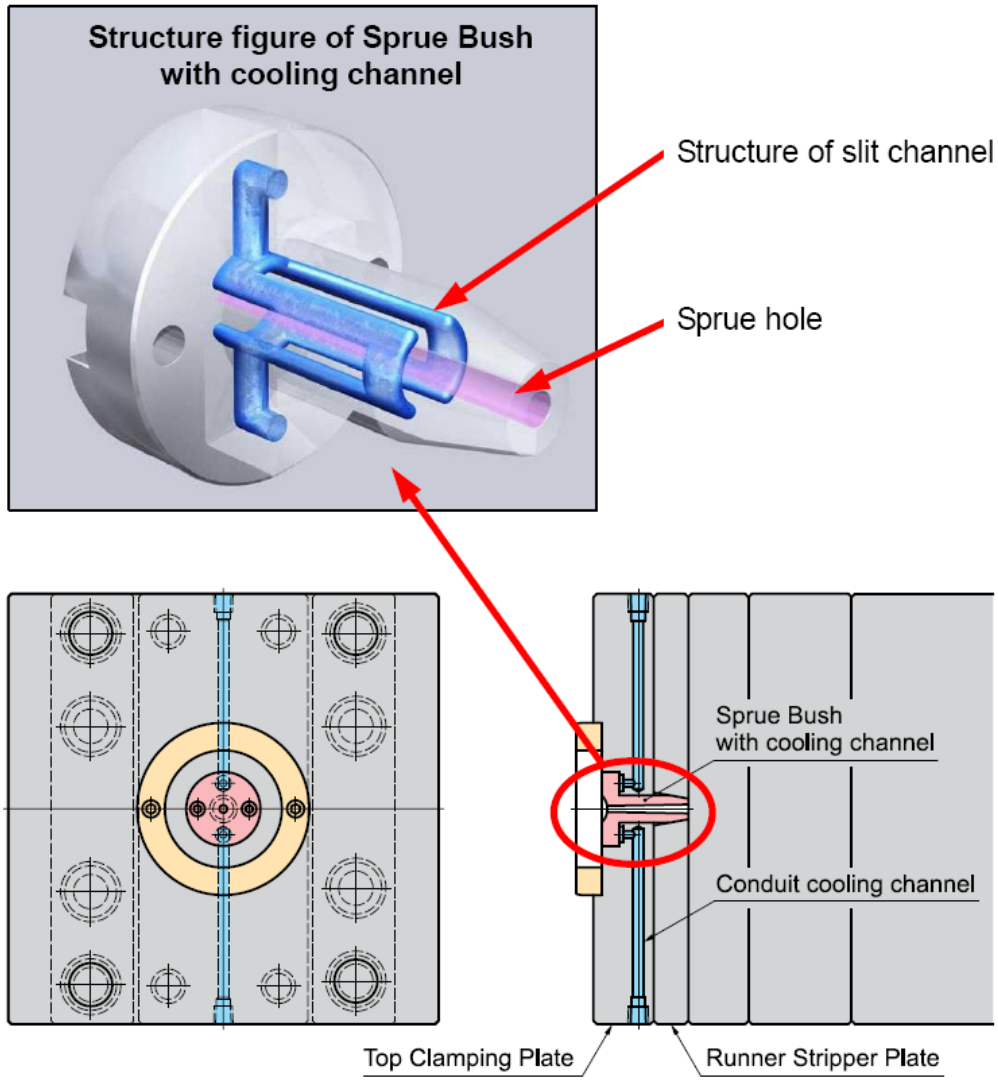


Figure 5.5: Structure Configure of Sprue Bush with Cooling Channel (www.opmlab.net)

5.2.3 The Merits of Sprue Bush with Slit Cooling Channel

There are many merits of sprue bush with slit cooling channel, of which are as follows:

1. High-cycle molding

- Reducing the cooling time.

2. Cost reduction

- Improving Production efficiency.
- Reducing Power consumption.

3. For trouble-free molding and durability improvement

- Mold temperature controlling and stringiness-preventing.

4. Using the latest technology “Selective laser sintering with milling method” to manufacture the sprue bush with cooling channel. They achieved to make slit-type cooling channel inside the spure bush by using “Selective laser sintering with milling method”.

5.3 The Application of Method Proposed in Sprue Bush

In this section, we provides case studies via numerical analysis to show how to design the cooling channel in sprue bush by applying the method proposed. The analysis model is shown in Figure 5.6. the material property and process conditions are shown in Table 6.1 and Table 6.2, respectively.

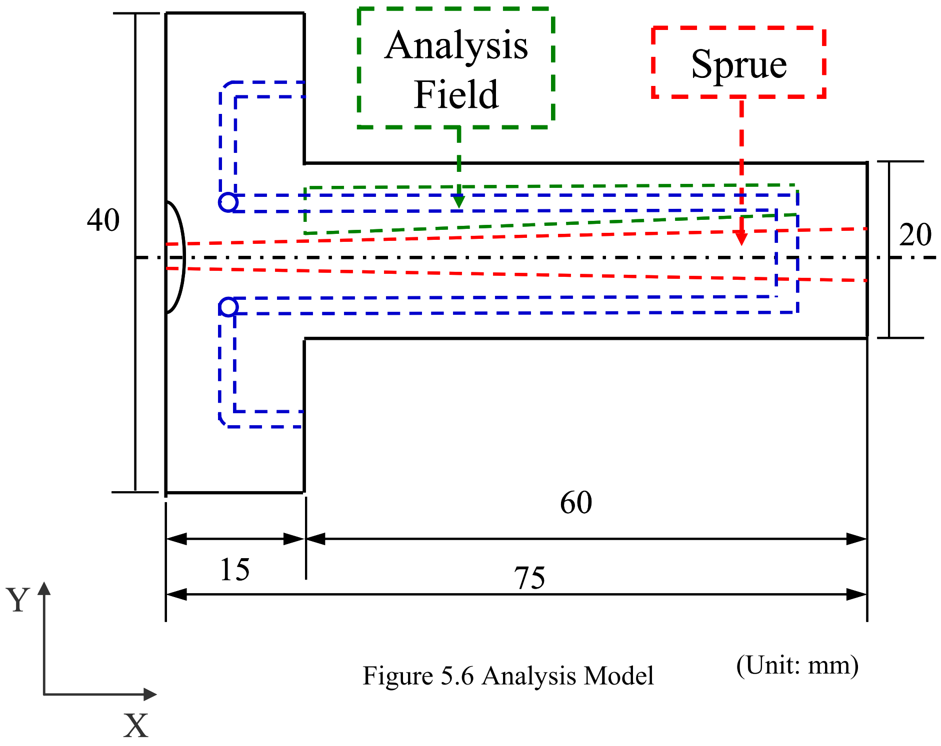


Figure 5.6 Analysis Model

Table 5.1: Material Property

PP	Thermal conductivity (W/m・K) Specific heat (J/kg・K) Density (Kg/m³) Filling temperature (℃)	0.3505 1433 1430 190
Sintered Body	Thermal conductivity (W/m・K) Specific heat (J/kg・K) Density (Kg/m³) Temperature (℃)	10.6 470 8000 40
Coolant (Water)	Thermal conductivity (W/m・K) Specific heat (J/kg・K) Density (Kg/m³) Temperature (℃)	0.6 4180 1000 25
Sintered Body	Injection Pressure (MPa) Elastic Modulus Density (Kg/m³) Poisson Ratio	113 1.3E+011 8000 0.33

Table 5.2: Process Conditions

Process Conditions	
Individual Number	20
Individuals by Crossover	50%(10)
Individual by Mutation	10%(2)
Weight Coefficient	0.5
fitness of the best individual and all individuals do not change (Finish Condition)	20 generations continue
The Maximum Generation Number	100

5.4 Result Analysis

We compared without cooling channels, cooling channel and optimization cooling channel in temperature so as to verify the effectiveness of proposed method. Optimization Cooling Channel of Sprue Bush, Cooling Channel and Without Cooling Channel of Sprue Bush are shown in Figure 5.7 and Figure 5.8, respectively.

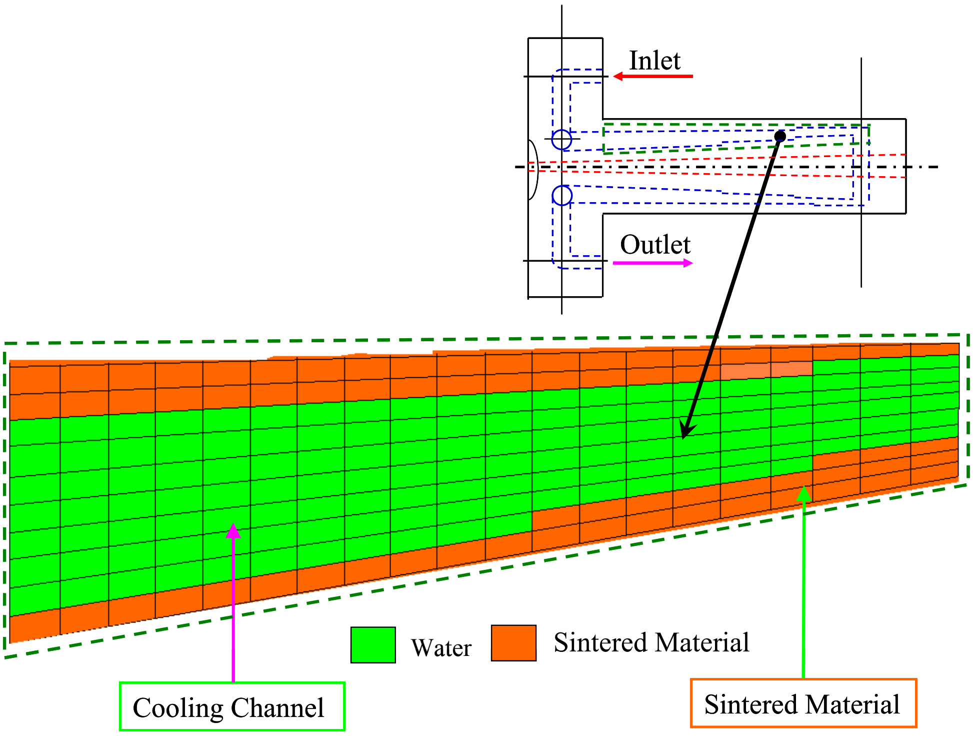


Figure 5.7: Optimization Cooling Channel of Sprue Bush

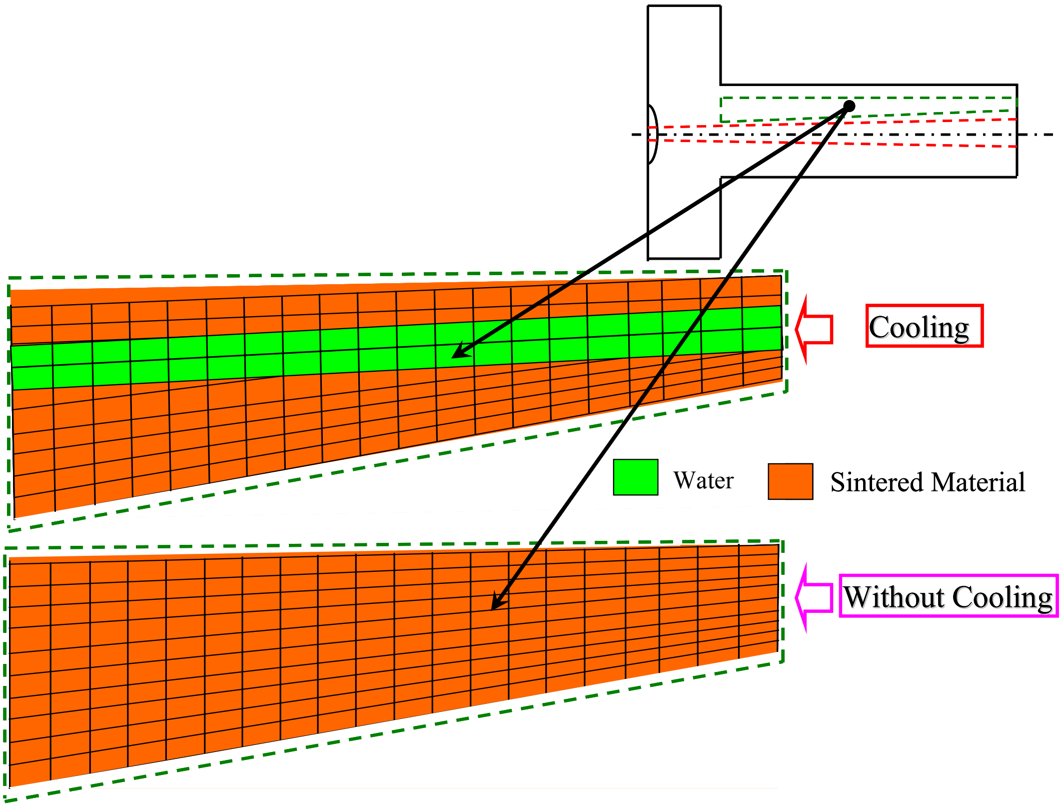


Figure 5.8: Cooling Channel and Without Cooling Channel of Sprue Bush

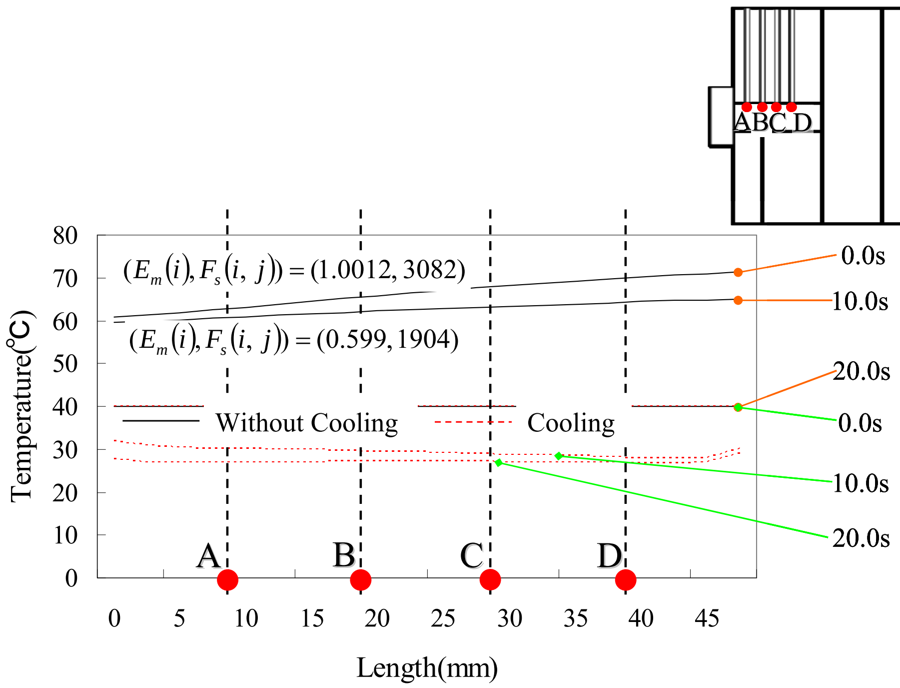


Figure 5.9: Points A, B, C and D Temperature Distribution without Cooling and Cooling

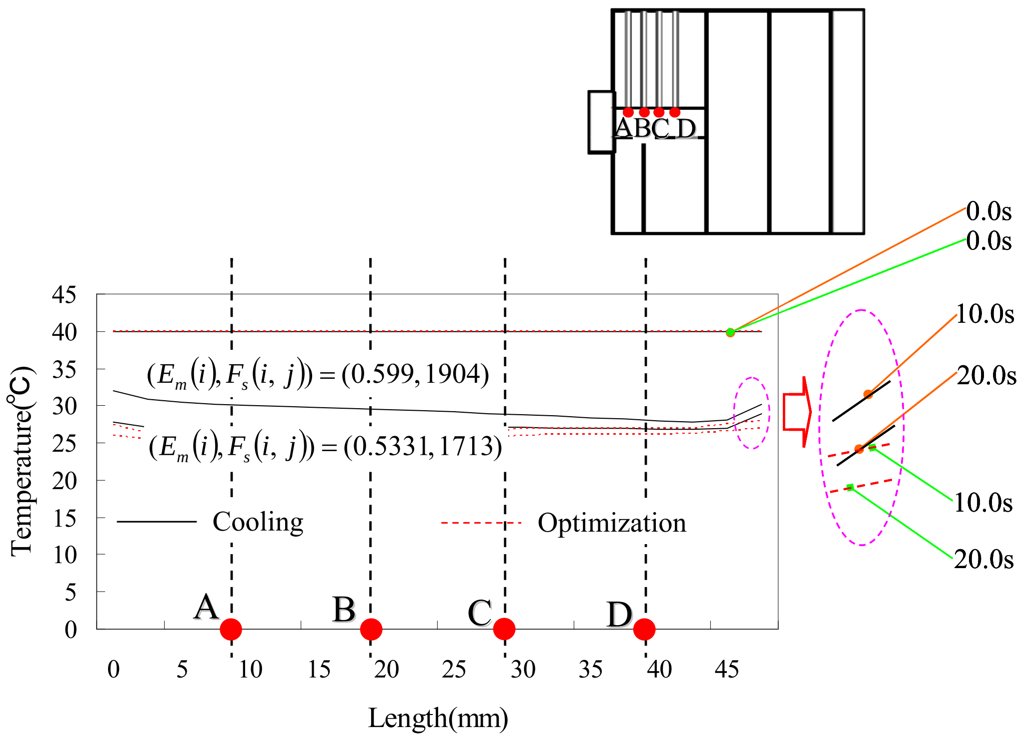


Figure 5.10: Points A, B, C and D Temperature Distribution Cooling and Optimization

We compared the temperature distribution on the evaluation curve in the cases of the without cooling channel and the cooling channel, the cooling channel and the optimized cooling channel. Figure 5.9 and Figure 5.10 show the temperature distribution on the evaluation point ABCD of sprue bush, taken at the time of 0, 10.0, and 20.0 seconds after the beginning of the cooling. The vertical ordinate in the graph is the temperature; the horizontal ordinate is the expanding length of sprue bush around the evaluated curve MNO.

In the Figure 5.9, the solid curves stand for the sprue bush without cooling. The dashed interval curves stand for the cooling channel. In the Figure 5.10, the solid curves stand for the cooling channel. The dashed interval curves stand for the optimized cooling channel.

The temperature of the evaluation point A is 62.5℃ (see Figure 5.9) at 20 seconds after the beginning of the cooling in the without cooling channel. The temperature of the evaluation point A is 26.89℃ when cooling finished for the cooling channel. There was a 35.61℃ difference between without cooling channel and the cooling channel sample at evaluation point A. The temperature of the evaluation point A is 26.89℃ (see Figure 5.10) at 20 seconds after the beginning of the cooling in the cooling channel. The temperature of the evaluation point A is 25.34℃ when cooling finished for the optimized cooling channel. There was a 1.55℃ difference between cooling channel and the optimized cooling channel sample at evaluation point A. From these results, the optimized cooling channel lowers the product surface temperature compared with that of the without cooling channel and optimized cooling channel as the cooling time increases.

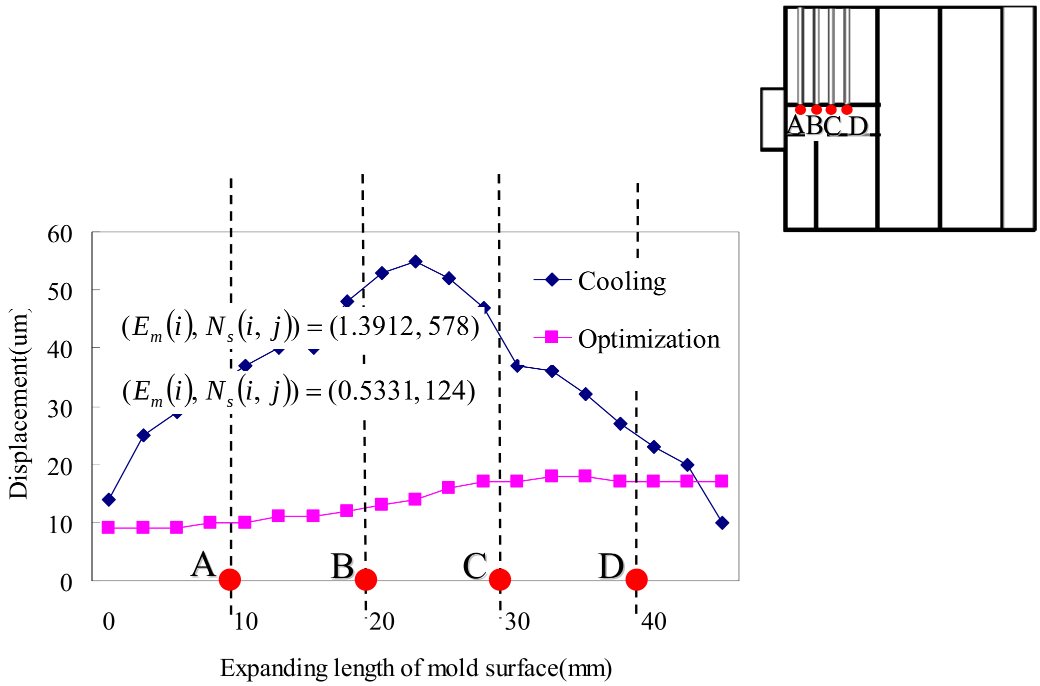


Figure 5.11: Deformation of Spure Bush Surface

We compared the deformation distribution on the evaluation curve for the optimization cooling channel and cooling channel. Figure 5.11 shows the deformation distribution on the evaluated points A, B, C, D. The vertical ordinate in the graph is the deformation; the horizontal ordinate is the expanding length of mold surface around the evaluated points A, B, C, D. According to this result, the maximum mold surface deformation with the optimized cooling channel is 17μm whereas the maximum mold surface deformation of the cooling channel is 55μm. The proposed optimization of the cooling channel can decrease the deformation of the mold surface.

5.5 Summary

In this chapter, by applying the propose methods and procedures on cooling channels automatic generation to numerical analysis, the evaluation of the give cooling channel is demonstrated.

Base on the result value of evaluation function, the method of making a proper design from initial given cooling channels is demonstrated.

The utility of the procedure of automatic generation for cooling channel is confirmed by the numerical analysis.

Through constructed cooling channel optimization, the convergence performance of the proposed method is confirmed.

For simulation results, the optimum size and shape of cooling channels can obtain the minimum evaluation value, and most even temperature distribution on product surface.

CHAPTER 6

6.0 Verification Experiment

In this chapter, molding experiment is carried out by using a designed sprue bush model. The results of investigation on the effects of different cooling channels, and the sprue surface temperature are measured and reported.

6.1 Experiment Introduction and Purposes

6.1.1 Introduction

As it has been stated in chapter 1, heat concentration inside plastic injection mold is one of the stubborn problems that cause the warpage, sink mark, and other deformation of molding products due to the variations of shrinkage rate in different parts of the product under an uneven cooling condition. If the heat from the resin is not taken out in an enough short time, it will be cumulated and lead to the heat concentration problem. Heat concentration causes uneven cooling to the molten resin in mold cavity and result in the imbalanced shrinkage which finally leads to molding defects due to the residual stress.

To effective cooling and prevent spring problem, one typical method is usually considered to arrange the cooling channels in the sprue bush. But this method is limited by the bush structure and machining cost.

In this research, different with the traditional method, how to evaluate, manage and control the heat in an injection mold are provided in chapter 2 and chapter 3. In this chapter, by applying the proposed method, the heat concentration problem and prevent spring corresponding cooling channels are investigated through molding experiments; also, the utility of proposed theory is verified by the experiment.

6.1.2 Experiment Design and Purposes

Several inspection items are chosen to evaluate the effects by using different cooling channels. Every design case is firstly confirmed by numerical analysis, and then the results are compared with the results of experiments. And the results and differences in resin cooling uniformity, temperature distribution of molding parts are demonstrated.

The experiment purpose can be summarized as following:

1. Demonstrates the application of how to use the proposed method and procedure to solve the heat related and prevent spring problem in sprue bush. Shows concrete examples of comparing different cooling channels and evaluate their performance on even cooling to the resin products. Provide the practical grounds for making an accurate cooling control and cooling channel design in a sprure bush.

2. Verify the utility of the proposed design method in sprue bush, and confirm the correspondence relationship of the simulation results and experiment results, also investigate the difference and applying range of the proposed method when used it in practical mold design.

3. Confirm the effects for reducing the heat concentration and prevent spring in a sprue bush by using the methods of placing cooling channels. Find out their features and differences during the cooling to resin products so as to be a guide or reference in actual applications by using above methods.

6.2 Theoretical Analysis and Evaluation Basis

The basic theory on cooling channel design has been discussed in chapter 3. Applying it in the experiments of this chapter, the numerical analysis for confirmation will focus on the temperature distributions on resin surface.

According to the cooling process of melt resin inside a sprue bush cavity, the resin solidifies from the resin surface where contacts the spure bush surface when the heat is transferred to the mold side. Temperature distribution and its variations surrounding this resin surface will decide the resin solidification process from the outer regions to the inner regions in the thickness direction of product walls. The evaluation function, which is defined in equation 2.3, reflects the above principle, it gives the evaluation values to describe cooling. Since evaluation values is an integration of temperature dispersions on the resin surface during the whole cooling process and deformation dispersions on the mold surface, therefore, among the different cooling channel designs, the one with a smaller gain in evaluation values means a good design for resin cooling uniformity. The evaluation for every cooling case in this chapter is conducted based on the evaluation values. The temperature distribution on resin surface is also discussed.

6.3 Experiment Cases and Investigation Items

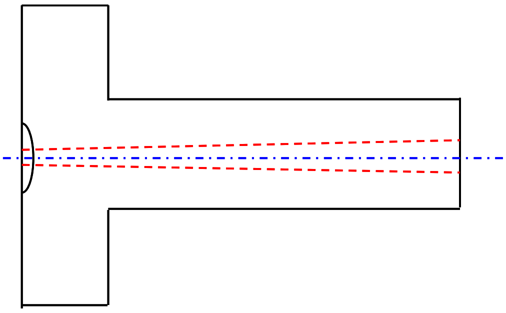
6.3.1 Cooling Design Cases

In order to compare the cooling effects and differences of the method, three experiment cases with different patterns of cooling channel in sprue bush are discussed. The concrete descriptions for those cases are listed in table 6.1, and their cooling channel images are shown in Figure 6.1

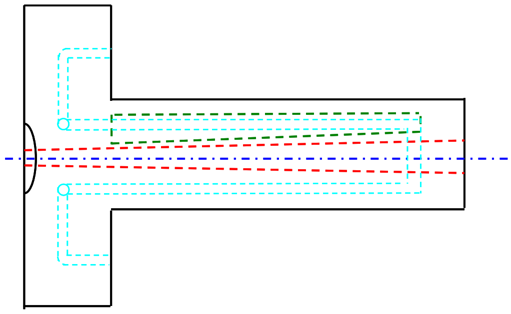
Case 1: No cooling channel

Case 2: Cooling channel

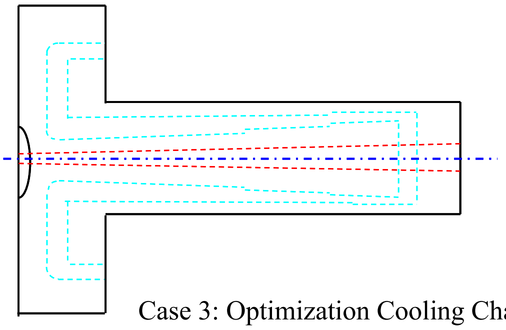
Case 3: Optimum cooling channel



Case 1: No Cooling Channel



Case 2: Cooling Channel



Case 3: Optimization Cooling Channel

Figure 6.1: Images of Three Experiment Cases

Table 6.1: Experiment Case Descriptions

Sprue Bush **A**	No cooling channel
Sprue Bush **B**	Cooling
Sprue Bush **C**	Optimization cooling channel

6.3.2 Investigation Items

This research investigated three major items on cooling effects by means of analysis and molding experiment.

a) Cooling Uniformity

Cooling uniformity is confirmed by simulations. Every cooling design case is first analyzed and evaluated by proposed evaluation function based on unsteady heat transfer and line static deformation. Dispersion of temperature distribution on resin surface is observed for calculating the value of evaluation function. The results describe the cooling uniformity of the cooling case in theory, and then it is compared with the results of molding experiment.

b) Resin Surface Temperature

Temperature of resin surface is the most direct parameter for describing cooling effect. It is difficult to understand the temperature vibrations on resin surface over whole cooling process via experiment. This research test the temperature of sprue bush where is 1mm distance far from resin surface.

6.4 Molding Experiment

6.4.1 Product Model and Experiment Mold

Product Model, experiment mold and temperature measurement points are shown in Figure 6.2, Figure 6.3 and Figure 6.4, respectively.

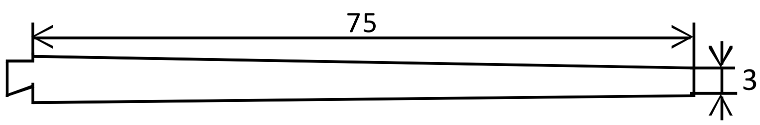


Figure 6.2: Product Model Unit [mm]

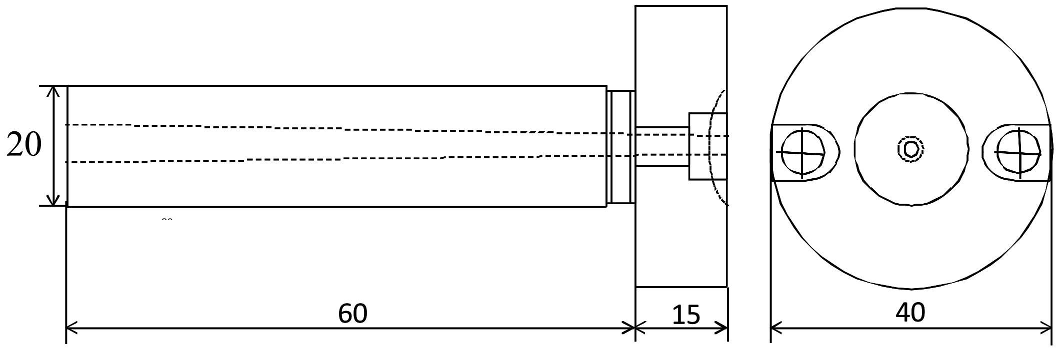


Figure 6.3: Experiment Model Unit [mm]

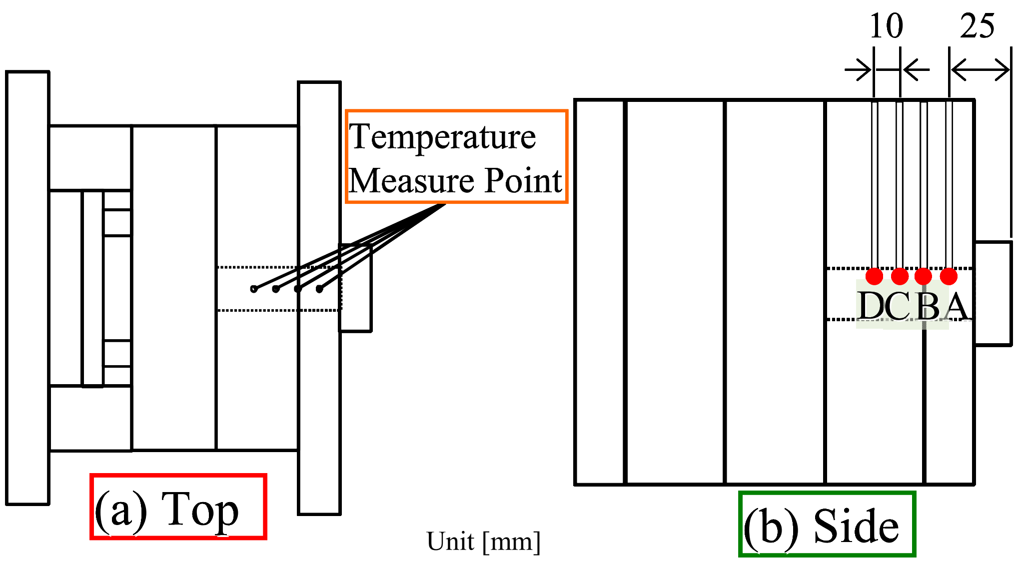


Figure 6.4: Temperature Measurement Points

6.4.2 Equipment and Molding Conditions

The molding machine used in this experiment is a 75-ton hydraulic molding machine (NIGATA, NN75SH7000). The overall cycle time is controlled at 30 seconds, cooling time takes 15 seconds. The temperature of injection cylinder is 190℃. The cooling water is maintained at 25℃, and the mold temperature in a steady running is 40℃, the whole experiment is conducted in a room temperature environment of 20℃-24℃.

6.5 Molding Experiment

Figure 6.5 shows the molding machine (Matsuura Seisakusyo. Ltd) and molding conditions are shown in Table 6.2. Experiment mold and sprue products are shown in Figure 6.6 and Figure 6.7, respectively.

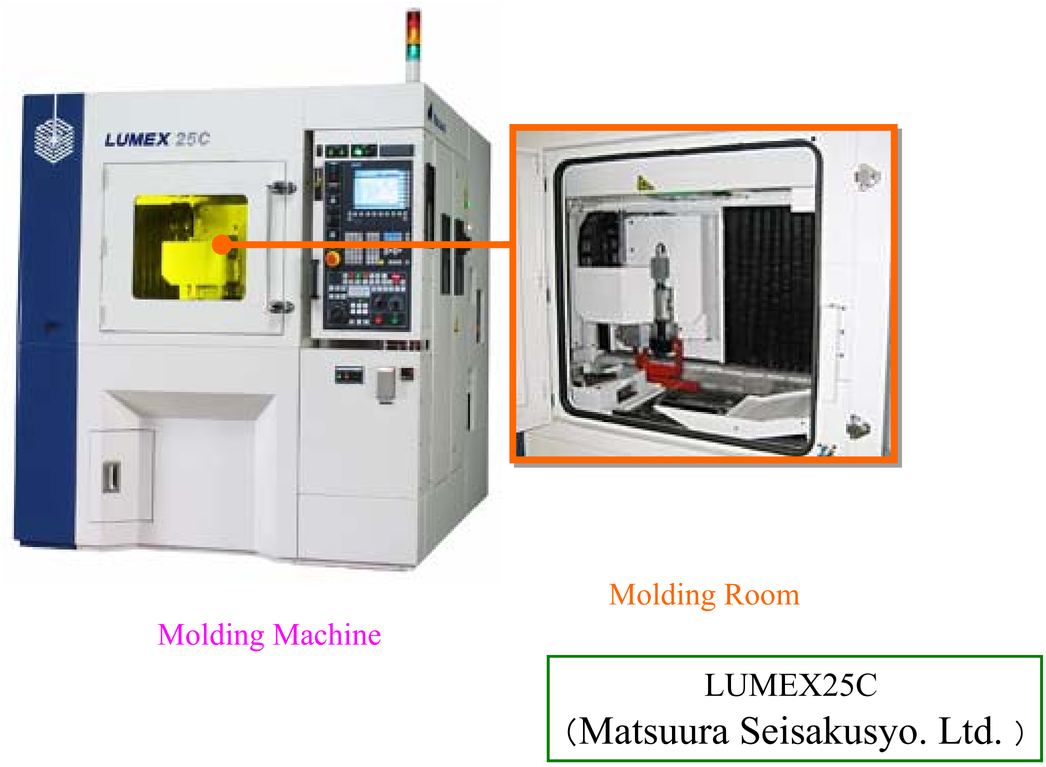


Figure 6.5: Molding Machine

Table 6.2 Molding Conditions

Laser Type	CO_2 Laser
Laser Maximum Power [W]	500
Maximum Rotation of Axis [rpm]	50,000
Maximum Product Dimension [mm]	250 × 250 × 185

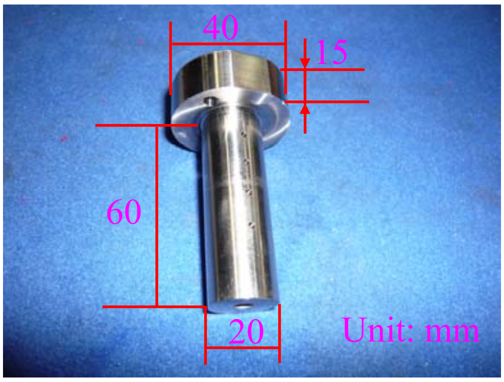


Figure 6.6: Experiment Mold

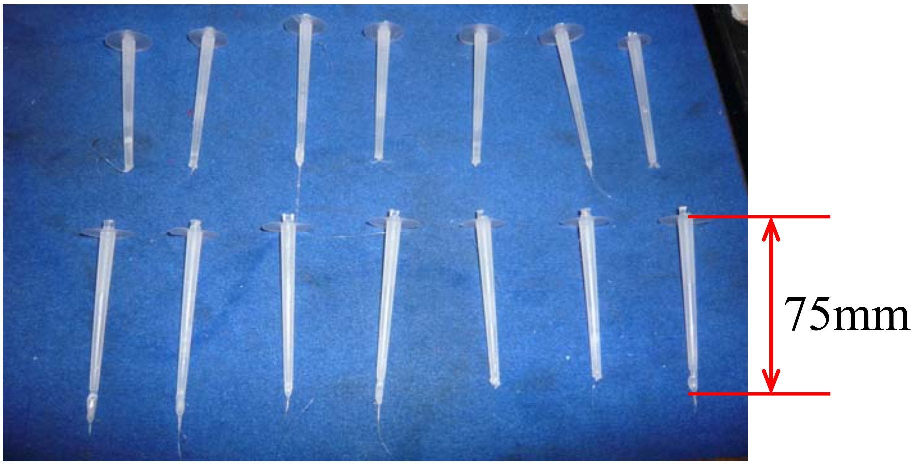


Figure 6.7: Sprue Products

Figure 6.8 shows the experiment overview. The labview, which is shown in Figure 6.9 is a measurement instrument (NATIONAL INSTRUMENTS, NI SCX1-1000), is used for measuring the temperature of sprue bush. Labview is a graphical programming environment used by millions of engineers and scientists to develop sophisticated measurement, test, and control systems using intuitive graphical icons and wires that resemble a flowchart.

Figure 6.8: Experiment Overview

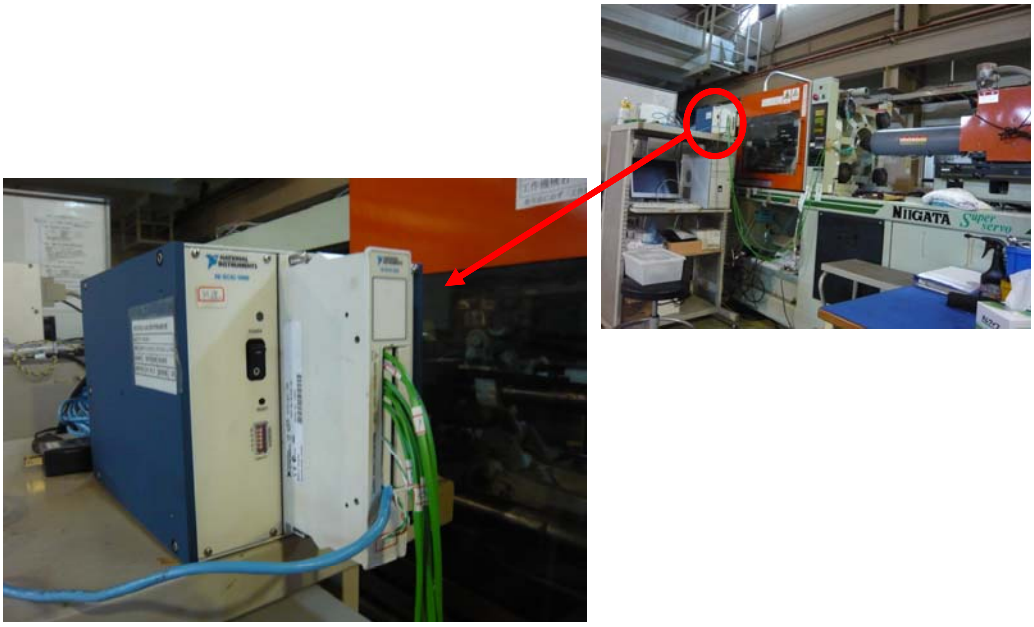


Figure 6.9: Labview

6.6 Results and Discussions

Figure 6.10, 6.11, and 6.12 show the temperature distribution on the sprue bush ABCD of the three cases, which are caught at the timing of 3500 seconds after the start of the cooling, the temperature increase company with cooling. Points A,B,C,D temperature distribution with optimization cooling channel are lower than that of without cooling channel and cooling channel in sprue bush. Figure 6.13 shown point A temperature distribution at the timing of 3500 seconds after the start of the cooling. From this result can understand, both cooling channels can decrease the sprue bush temperature, optimum cooling channel is more effective.

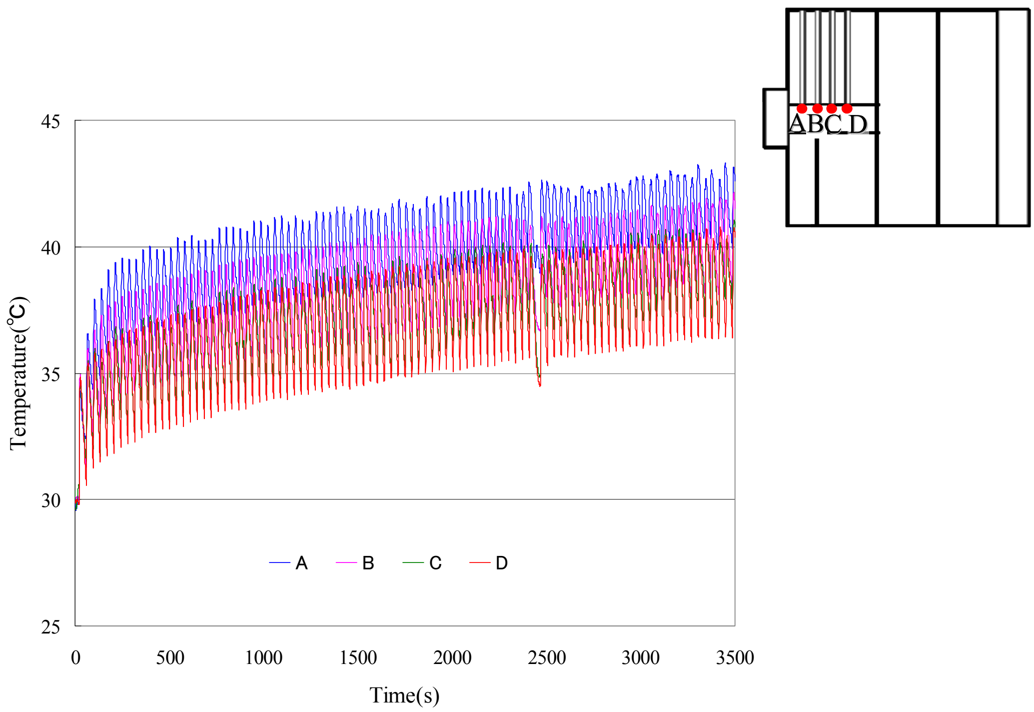


Figure 6.10: A, B, C, D Temperature Distribution Without Cooling Channel

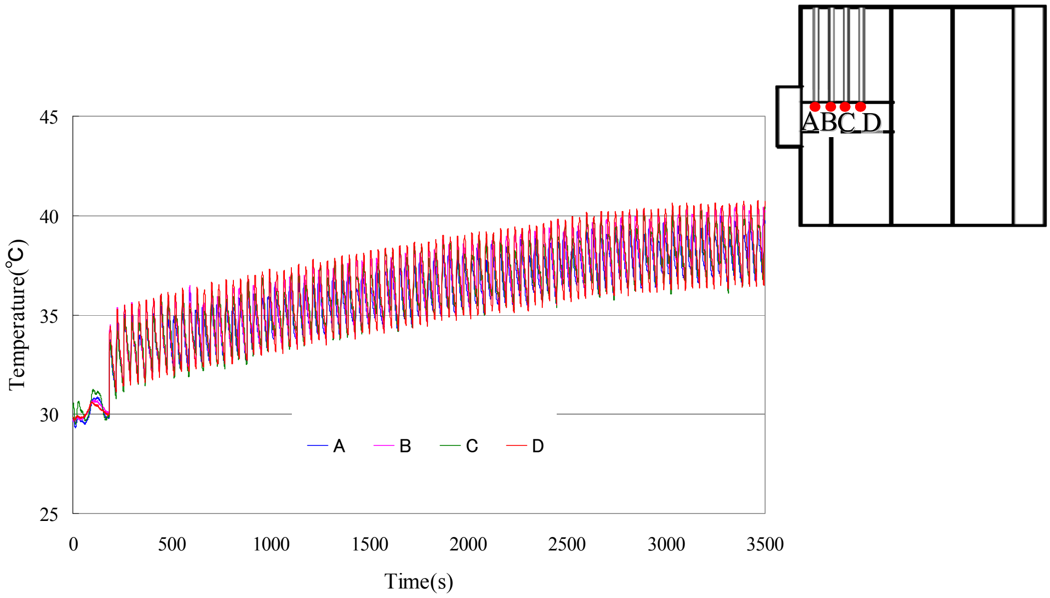


Figure 6.11: A, B, C, D Temperature Distribution With Optimization Cooling Channel

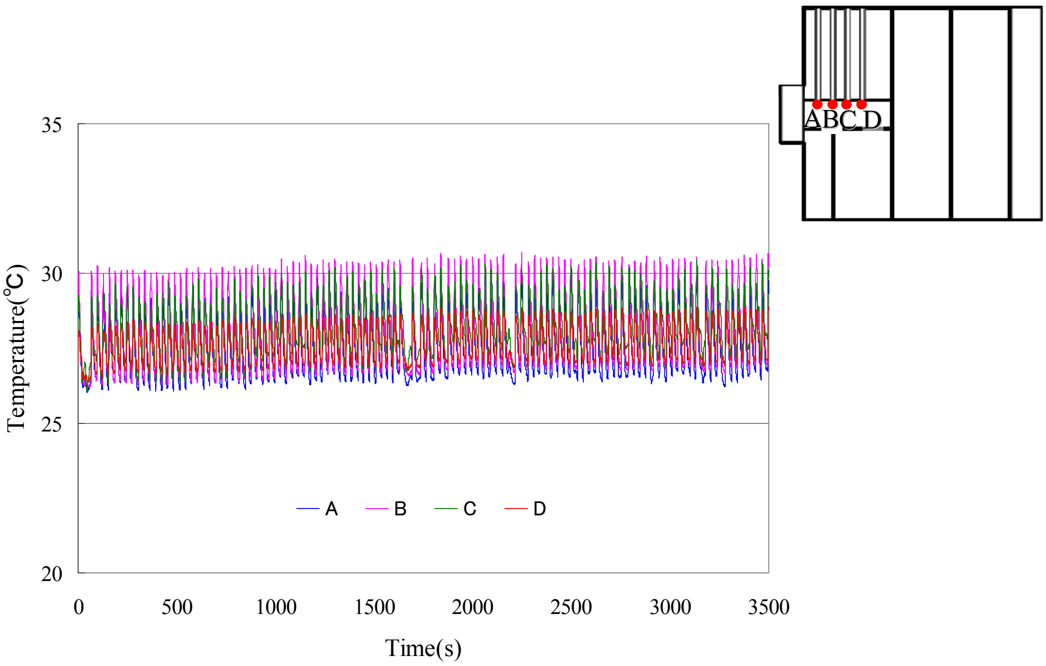


Figure 6.12: A, B, C, D Temperature Distribution With Cooling Channel

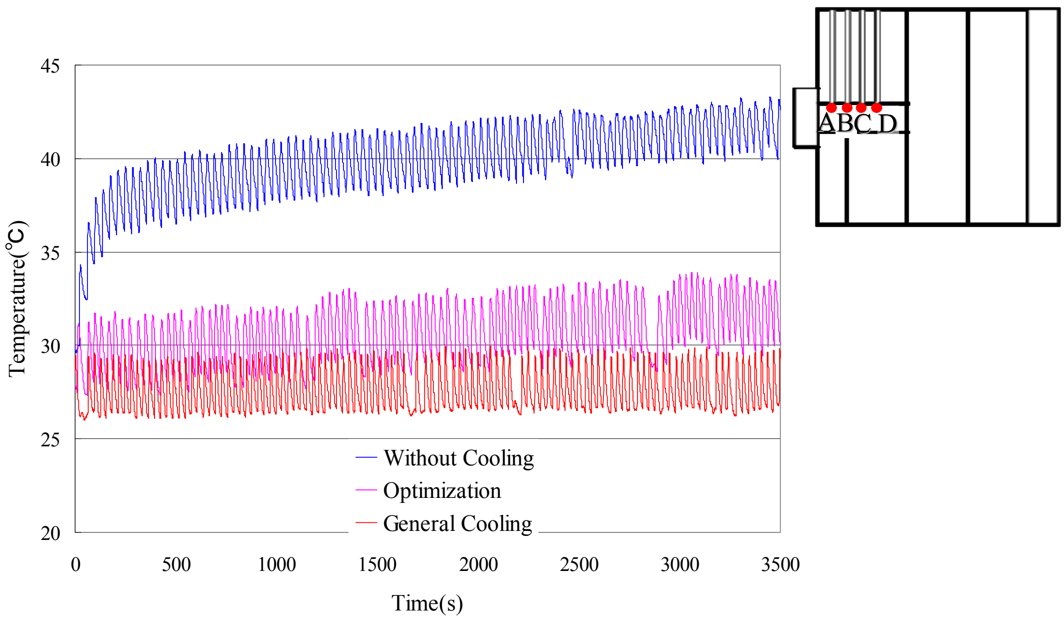


Figure 6.13: Point A Temperature Distribution Without Cooling Channel, Optimization Cooling Channel, and Cooling Channel

According to measuring data of molded sample, when use cooling channel inside the sprue bush, a further decrease of temperature is confirmed comparing with the result in numerical analysis. This can be considered as the effect of the reinforcement of the cooling when added cooling channels in the sprue bush. In the numerical analysis, the heat resistance between the resin and mold material is assumed as zero. But in actual experimental mold, the heat resistance at the boundary is not zero, heat transfer also is not in an ideal condition, it is slower than the simulation. so, the above result in the experiment can be understood as the "compensation" to lose of heat transfer speed due to the heat resistance between the resin and mold material.

We can see that the evaluated points A, B, C, D temperature of the sprue bush with cooling channel is more lower than that of the sprue bush with optimization cooling channel from figure 6.13. As a result, we think that it is reason of sticking-out sintering when sprue bush is formed, this is shown in figure 6.14. The volume of water flowing will become small for sticking-out sintering.

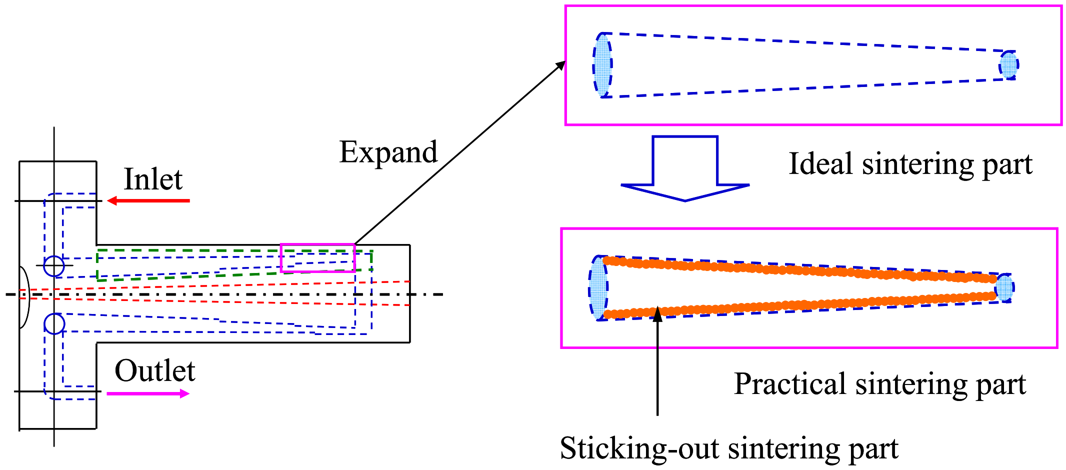


Figure 6.14: Ideal Sintering Part and Sticking-out Sintering Part

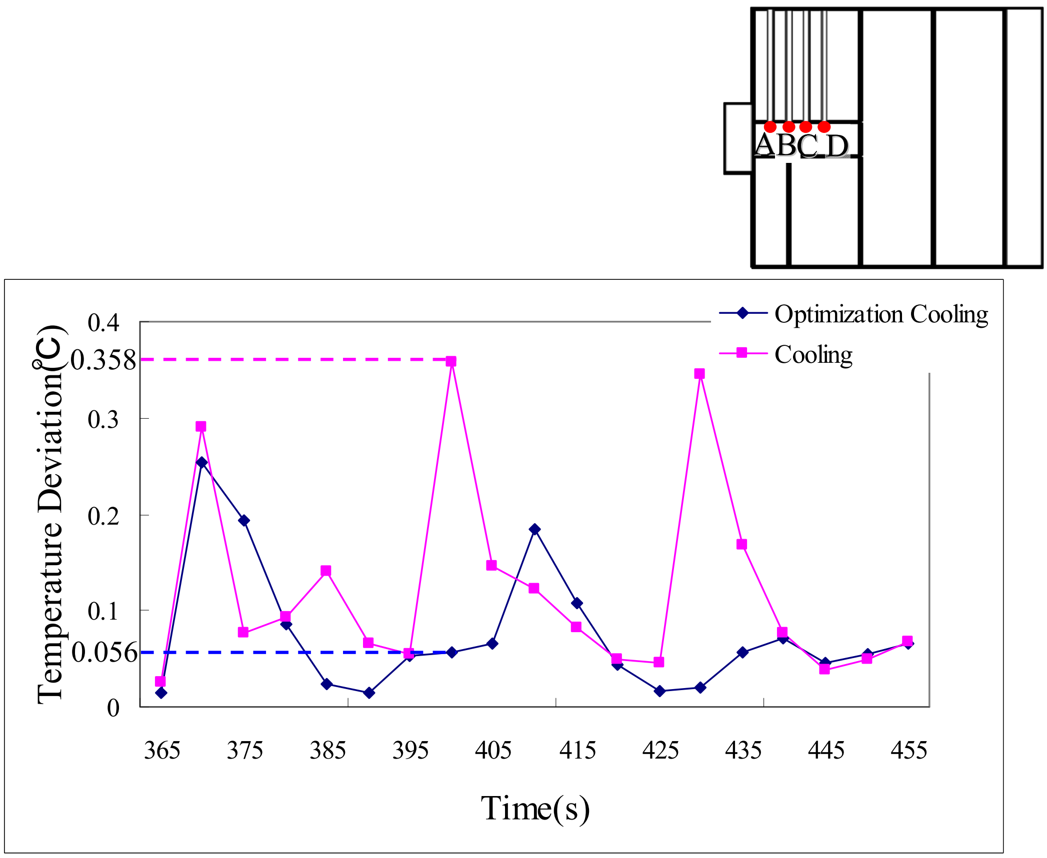


Figure 6.15: Temperature Dispersion of the Sprue Bush with Optimization Cooling Channel and Cooling Channel

We compared the temperature dispersion of the sprue bush with optimization cooling channel and cooling channel. Figure 6.15 shows the temperature Dispersion in some cooling time. The vertical ordinate in the graph is the temperature dispersion; the horizontal ordinate is the time fom cooling start. According to this result, there is a smaller temperature dispersion of optimization cooling channel in the sprue bush compare with cooling channel.

.

6.7 Summary

The experiment verified the utility of the proposed cooling channel design method based on resin cooling uniformity.

Numerical analysis and molding experiment are conducted to verify the cooling effects of cooling channels.

Both methods can decrease temperature dispersion in sprue bush and improve cooling effect. Optimum cooling channel gained more effective result.

Experimental data shows the best result when apply optimum cooling channel inside the sprue bush.

A difference on temperature result exists between the analysis and molding experiment in sprue bush areas, this is result from the heat resistance in actual molding experiment and some others forming reasons.

Chapter 7

7.0 Conclusions

This chapter concludes the entire thesis and discusses the future tasks of this research.

7.1 Conclusions

This research aims the proper design of the multiple-purpose cooling channels total Design based on rapid prototpying method using genetic algorithms (GAs). By using the proposed concept, this research provided a set of description, evaluation, design methods to realize an ideal cooling channel, which is able to make an even cooling to the resin in an injection mold and prevent spring in sprue bush. Through numerical analysis and practical molding experiments, the utility of the proposed method was verified.

The conclusions can be summarized from each chapter as following:

In chapter 2, propose a new definition, to handle cooling problems in an injection mold and gave its detail explanations, also the evaluation method.

1. The fundamental concept is defined based on the analysis of heat transfer process in an injection mold.

2. By using the concept of cooling, it is possible to recognizing, evaluating and arranging the cooling related problems in injection molds.

3. An evaluation method is defined by watching the resin cooling uniformity during its whole cooling process. Evaluation function is proposed to estimate the heat state and varisions in an injection mold, and it reflects the solidification status of the resin in mold cavity.

4. The evaluation function for cooling can be applied both in two or three dimensional mold.

In chapter 3, solved the problem of how to design an ideal cooling channel based on the evaluation of resin cooling uniformity and mold deformation small in a plastic injection mold and provided the related algorithm and procedures.

1. The design methods of how to automatic generate a cooling channel in plastic injection molds is discussed, and the related algorithm is demonstrated.

2. Based on the evaluation function proposed in Chapter 2, the design procedure for cooling channel automatic generation is developed in an injection mold.

3. Using the evaluation function as the governing function, by minimizing the evaluation value, the concrete algorithm for automatic generation of cooling channel is provided.

In chapter 4, through the numerical analysis, confirmed the proposed design method of cooling channels.

1. By applying the propose methods and procedures on cooling and deformation to numerical analysis, the evaluation of the give cooling channel is demonstrated.

2. Base on the result value of evaluation function, the method of making a proper design from different initial cooling channels is demonstrated.

3. The utility of the procedure of automatic generation for cooling system is confirmed by the numerical analysis.

4. The cases of automatic generation under the condition of initial shape changing and without optimum shapes are confirmed.

5. For simulation results, the optimum size and shape of cooling channel can obtain the minimum evaluation value, and most even temperature distribution on resin surface, most smallest deformation distribution on mold surface.

In chapter 5, through the other numerical analysis, confirmed the proposed design method of cooling channels.

1. By applying the propose methods and procedures on cooling and deformation to numerical analysis, the evaluation of the give cooling channel is demonstrated.

2. The utility of the procedure of automatic generation for cooling channels are confirmed by the numerical analysis.

3. The cases of automatic generation under the condition of initial shape changing and without optimum shapes are confirmed.

4. For simulation results, the optimum size and shape of cooling channel can obtain the minimum evaluation value, and most even temperature distribution on resin surface, most smallest deformation distribution on mold surface.

In chapter 6, verified the utility of the design method of cooling channel by actual molding experiments.

1. The experiment verified the utility of the proposed cooling channels design method based on resin cooling uniformity.

2. Numerical analysis and molding experiment are conducted to verify the cooling effects of cooling channels on sprue bush areas.

3. Both methods can prevent spring in sprue bush areas and improve cooling uniformity, optimum cooling channels gained more effective result.

4. Experimental data shows the best result when apply optimum cooling channel inside the sprue bush.

5. A difference on temperature result exists between the analysis and molding experiment in the sprue bush areas, this is result from the heat resistance in actual molding experiment.

Traditionally, mold technology is strongly depended on practical experiences, this leads to the result of that many design principles in this field are from experiences. But the situation is not fit for requests of today's advanced molding technology, which are usually mentioned as the high precision, fine formability, low cost and efficient productivity, new design method based on reasonable theoretical ground is demanded.

The proposed method on cooling channel design in plastic injection mold is based on the evaluation of resin cooling uniformity, and it is verified by numerical analysis and molding experiment, the utility can be expected in the applications to practical mold designs.

7.2 Future tasks

The most fundamental works, which include concept definition, procedure proposition, numerical analysis and molding experiment verification etc. have been finished, it is still a distance to the actual application for molds design. The future tasks can be summarized as several major aspects:

1. One left problem is that, the proposed method is developed for the objective model, which is supposed as a thin and equal wall thickness product, for an uneven wall thickness product, it need a different evaluation method for the uneven heat transfer speed crossing the wall thickness.

2. The proposed evaluation function considered only the surface temperature distribution of the resin, surface deformation of the mold, and used it for the evaluation function definition, the affections of temperature distribution in the inner part of the resin area, deformation distribution in the inner of mold, need to be confirmed.

3. Numerical analysis and molding experiment used a simple shape product, but the actual plastic products are various, and most of them have the complicated geometrical shapes. How to apply the basic rules in this research to the common products, and how to make the solutions convergence in complicated situations, will be hard tasks in this field.

4. Due to machine conditions and machining costs, the molding experiment chosen sprue bush. The experiment gave the results of confirmations for assigned cooling systems, but for the optimum cooling channels in the mold, the thermal effects still need the experimental verifications.

5. Experiment work used a simple sprue, but the most of them are a part of product. How to apply the basic rules in this study to the sprue, which has a complicated and irregular product, will be also hard works in the future.

Accompanying the solutions of the above items, it is able to expect more effective results on handling, evaluation and design of cooling channel problems in plastic injection molds.

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