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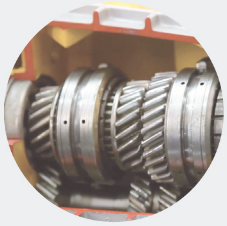

Reduction of scrap percentage of cast parts by optimizing the process parameters

RAKESH CHANDRASEKARAN

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POLITÉCNICO
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REDUCTION OF SCRAP PERCENTAGE OF CAST PARTS BY OPTIMIZING THE PROCESS PARAMETERS

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REDUCTION OF SCRAP PERCENTAGE OF CAST PARTS BY OPTIMIZING THE PROCESS PARAMETERS

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Dissertation presented to ISEP – School of Engineering to fulfill the requirements necessary to obtain a Master of science degree in Mechanical Engineering, carried out under the guidance of Raul Duarte Salgueiral Gomes Campilho and co-guidance of Francisco Jose Gomes da Silva.

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KEYWORDS

Casting, Die-casting, Aluminium, Scrap rate, Process optimization, Design of Experiments, ANOVA analysis, Numerical simulation.

ABSTRACT

Casting is a widely used manufacturing process in the automotive industry. Die casting is the most popular type of casting processes. But the fact observed in many industries is the scraps or wastages occurring after the process.

Thus, this thesis is primarily based on understanding the die-casting process and the factors governing them. In this study, the part to be studied is a throttle body. The raw material used for the production is AlSi9Cu3.

The main concern in this part is the occurrence of defects such as bad filling, heat bubbles, and porosity. Thus, it is important to perform process optimization. Techniques or methods such as Design of Experiments, ANOVA analysis, and numerical simulations are used. This thesis also focuses on the use of brainstorming as an industrial discussion tool and the use of quality tools for process optimization. Thus, these techniques are utilized in order to eliminate the defects. The scrap after using these techniques and methods is reduced to 9% from 14% initially found.

This investigation has been performed as a continuous improvement project in Sonafi and as a master thesis for “Instituto Superior de Engenharia do Porto”.

PALAVRAS-CHAVE

Fundicao, Fundicao em molde, Taxa de refugo, Otimização de processos, Desenho de Experiências, Analise ANOVA, Simulação numérica.

RESUMO

A fundição é um processo de fabrico amplamente utilizado na indústria automóvel. A fundição injetada é o tipo mais popular de processos de fundição. Mas, o facto observado em muitas indústrias é o aumento de sucatas ou desperdícios que ocorrem após o processo.

Assim, esta tese é baseada principalmente na compreensão do processo de fundição e nos factores que a governa. Neste estudo, a parte a ser estudada é um corpo do acelerador. A matéria-prima usada para a produção é AlSi9Cu3.

A principal preocupação nesta parte é a ocorrência de defeitos como mau preenchimento, bolhas de calor e porosidade. Assim, é importante realizar a otimização do processo. São utilizadas métodologias como o Desenho de Experiências, análise ANOVA e simulações numéricas. Esta tese também se concentra no uso do *brainstorming* como uma ferramenta de discussão industrial e uso de ferramentas de qualidade para otimização de processos. Assim, essas técnicas são utilizadas para eliminar problemas o corridos na produção.

Esta investigação foi realizada como um projeto de melhoria contínua na Sonafi e como uma tese de mestrado para o Instituto Superior de Engenharia do Porto.

LIST OF SYMBOLS AND ABBREVIATIONS

List of abbreviations

ANOVA	Analysis of Variance
CNC	Computer Numerical Control
DOE	Design of Experiments
DOF	Degree of Freedom
FEM	Finite Element Model
HPDC	High Pressure Die Casting
NADCA	North American Die Casting Association
QC	Quality Control
SN	Signal to Noise Ratio

List of symbols

%	Percentage
€	Euro

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INTRODUCTION

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1 INTRODUCTION

1.1 Framework

The difficulties that are often occurring in the business environment, resulting from the rapid development of technologies, intense global competition, and demanding customer expectations need the companies to meet the demands of the markets.

Foundry industries are developing and having a major impact on the economy of automotive industries. Die casting operations have become complex, leading to the occurrence of defects. The die-cast design and parameters must be designed perfectly to reduce the manufacturing defects. This thesis is a concept in analyzing the process with various methods and determining the best level of the parameters.

1.1.1 A brief description of casting and die-casting in particular

Casting is growing to be one of the prominent manufacturing processes in modern days. The importance of the casting process is discussed in section 2.1.1 (Importance of castings in the worldwide economy). Almost all the parts of a car are manufactured through different casting processes such as die casting, sand casting, and investment casting. Casting is a manufacturing process in which, a molten metal is poured into a cavity which is in the shape desired by the customer and allowed to cool and solidify. This process can be carried in varied forms, thus giving birth to processes such as die-casting, investment casting, sand casting, gravity casting and so on. Here, the die-casting process is considered for the thesis.

1.1.2 A brief description of DOE, Taguchi analysis, ANOVA and numerical simulation

In order to perform the thesis, some important strategies were deployed. It includes DOE and ANOVA. DOE is abbreviated to Design of Experiments and ANOVA is Analysis of Variance. DOE is a proven method in the die casting industry to determine the relationships between different parameters affecting the process and also on the output. Taguchi analysis is a type of experimental design used to ensure good results at the time of design phase. ANOVA is a statistical process aimed at determining the relation between the parameters and also on determining the main influential parameter. For further detailed analysis, numerical simulation is a method widely used to understand the behavior of the process at different conditions.

1.2 Main goals

The main goals of this thesis are as follows:

- To understand the die casting process utilized by the industry;
- To analyze and determine the type of defects occurring in the casting;
- To analyze and determine the causes and remedies relating to the defects and thus, reducing the defect percentage.

1.3 Methodology

The method used in the project consists of six stages. Each stage consists of important progresses that occur during the project.

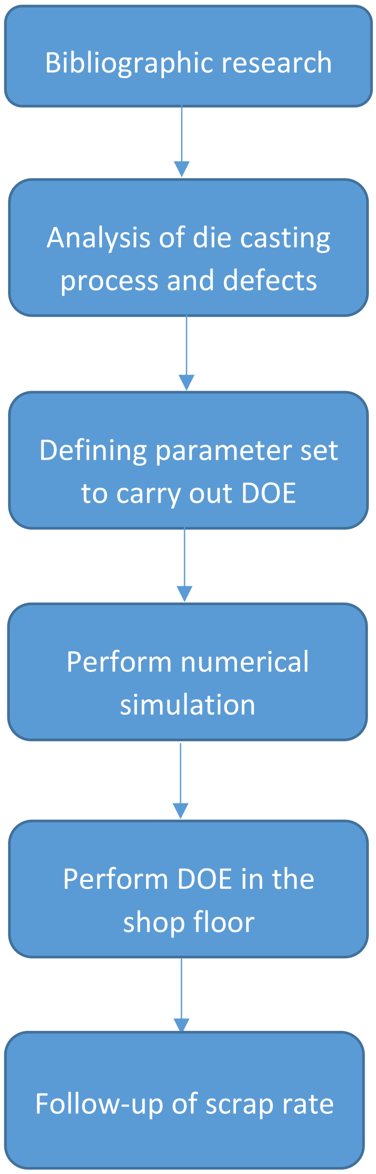


Figure 1 Methodology used in the thesis in the form of flow chart

- Stage I: Bibliographic research on the area of the project

Bibliographic revision of the respected topic is performed to analyze and contrast with the ideologies used by SONAFI.

- Stage II: Analysis of die casting process, type of defects and useful solution

The analysis is carried out by using quality tools in determining the type of defects occurring and also determining the solutions.

- Stage III: Determining the parameters set for the Design of Experiments (DOE)

The third stage involved determining the set of parameters to carry out DOE. This set of parameters was found after the quality analysis of the defects and their solutions.

- Stage IV: Performing the numerical simulation

The critical parameters from the DOE were used to perform numerical solution in order to determine the effects of these parameters on the product.

- Stage V: Performing DOE in the shop floor

The set of experiments from DOE was used to perform real-time analysis on the die casting machine. The scrap rate for the DOE was determined and this result was used to analyze in MiniTab software to determine the best set of parameters.

- Stage VI: Follow-up of scrap rate

The final stage consisted of following-up of scrap rate for a period of one month.

1.4 Structure of the thesis

The thesis structure is as follows:

- The first part discusses the introduction to the die casting processes and the main goal and the methodology used in the experiment.
- The second part focusses on the background check about the casting process, mainly on the die casting process, the molds used and design rules and considerations. Since the thesis is focused on reducing defects, a literature review of the different defects, their causes, and the solutions are discussed. Then, a brief description of quality tools is reviewed. Followed by an insight into the design of experiment, statistics and numerical simulation is done;
- The third part deals with the development during the thesis. This phase consists of problem definition, brainstorming, SWOT analysis, preparation of DOE, ANOVA analysis and numerical modeling;
- The final part consists of the conclusion and future works.

1.5 Welcoming company

Sonafi is an Aluminum alloy die-casting company founded in 1951, aimed at the automotive sector. Sonafi develops and manufactures components for various applications with complex geometry, with technologies such as die-casting, machining, shot blasting or vibration machining, machining, sub-component assembly, leak testing, and other anti-error and recording tests, according to the specification agreed with the customer.

BIBLIOGRAPHIC WORK

2 THEORETICAL BACKGROUND

2.1 Casting processes

Casting is an engineering manufacturing process used for mass production, in which the mold is filled with molten material, where it solidifies. In this process, complex parts can be manufactured economically and rapidly that otherwise takes a long time by other processes such as shaping and cutting. The casting process can be utilized a large variety of parts that are used in different industries, ranging from a plastic toy to big turbine blades [1].

Selection of the casting process

The different casting process is utilized by different industries and its selection depends on a variety of factors such as [1]:

- The quantity of casting;
- Manufacturing cost;
- Product material;
- Dimensional accuracy needed;
- Surface finish needed.

2.1.1 Importance of castings in the worldwide economy

HPDC is particularly suitable for high production rates and it is applied in several fields and approximately half of the world production of light metal castings is obtained by this technology [2].

In 2016, the worldwide casting production was 104.4 million metric tons, that is 0.2% more compared to 2015 [3]. China has been the number one country in casting production in terms of tonnage capacity (Figure 2).

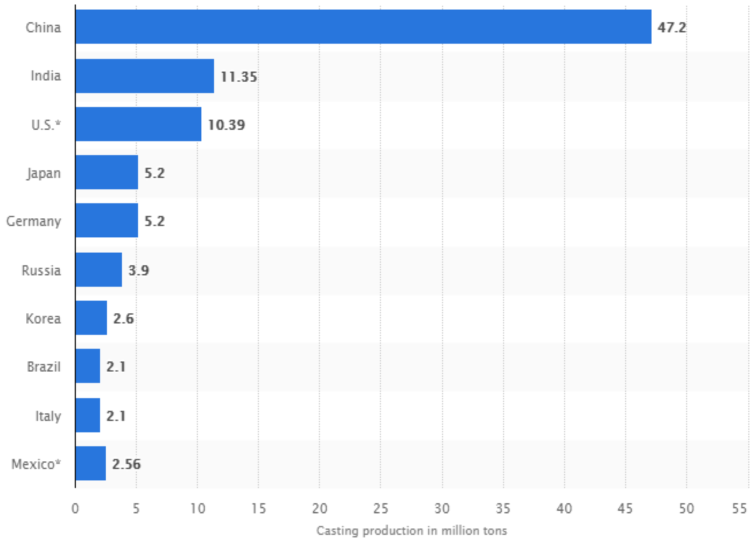


Figure 2 Casting production worldwide economy 2016 in million metric tons [4]

Figure 3 depicts the worldwide aluminum cast production and probable growth in the future. The main inferences from the figure are as follows:

- Germany has gained market shares, thus enhancing the economy of western Europe;
- China continues to be the highest in terms of production.

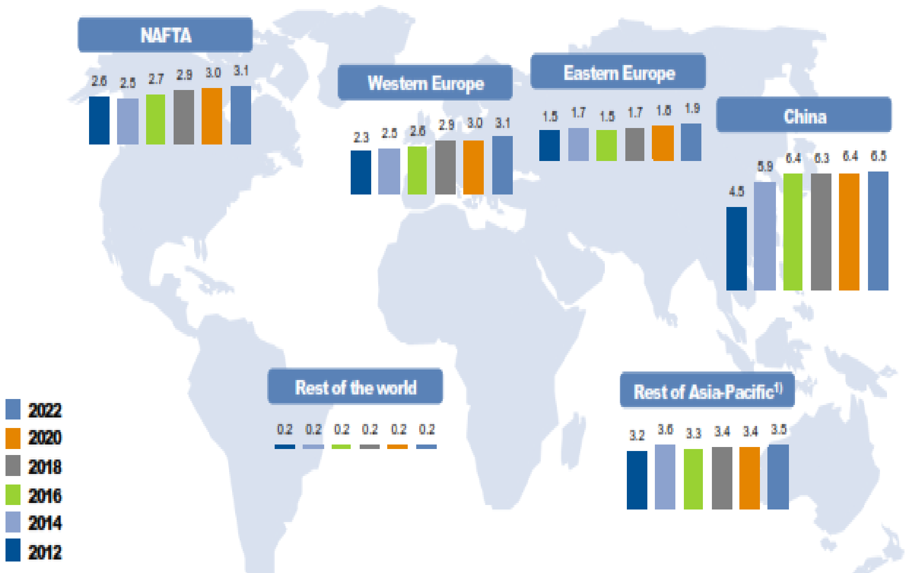


Figure 3 Global aluminum cast production (in million tons) [5]

2.1.2 Types of casting processes

The casting processes are divided into two main categories [6], namely (Figure 4):

A. Expendable mold casting;

B. Permanent mold casting.

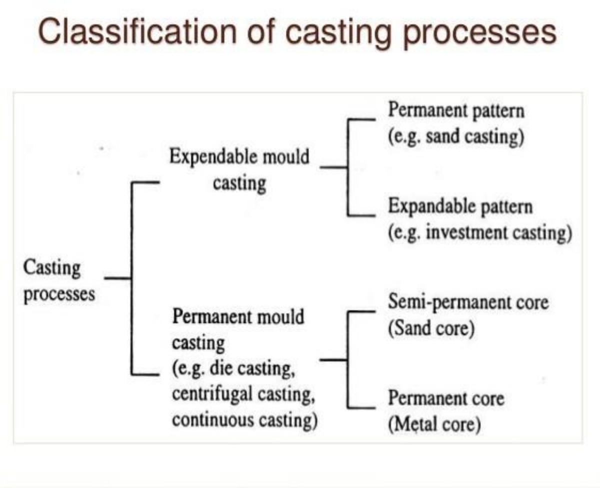


Figure 4 Classification of the casting processes [6]

A. Expendable mold casting

Expendable mold casting is the oldest and simplest casting process. The process involves creating a new mold for the casting, which cannot be reused again. The process depends on the type of pattern utilized.

I. Sand Casting

Sand casting is one example of an expendable mold casting process. Sand casting is one of the oldest casting processes. It can easily cast materials of high melting temperature such as Steel, Nickel, and Titanium [7].

1. The sand casting process is done with 6 steps, namely (Figure 5):
2. Place a pattern in the sand to create mold;
3. Incorporate sand and pattern in a gating system;
4. Remove the pattern;
5. Fill the mold cavity with molten metal;
6. Allow the metal to cool and solidify;
7. Breakaway the sand mold and remove casting.

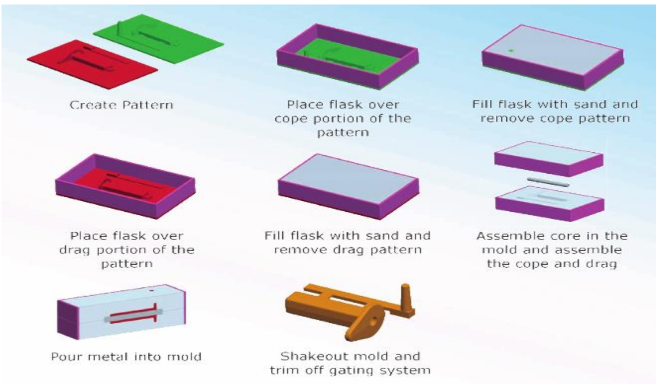


Figure 5 Steps in Sand Casting process [8]

Although the process consists of six steps, each step has preparations before the casting process is carried out. First, the pattern must be made. The pattern is a skeletal replica of the part that is produced but slightly larger in size than the original part. Different types of pattern material are used, such as wood, metal, and plastic. Each material has its own advantages and disadvantages. For example, wood is a user type of material, but it warps. Whereas, metal is expensive than others, but it tends to have a longer lifetime. Plastic is in between the other two aforementioned materials but has a very short lifetime [7].

Several types of patterns can be applied in sand casting. According to the application, the patterns are divided into (Figure 6):

- Solid pattern;
- Split pattern;
- Match and plate pattern;
- Cope and drag pattern.

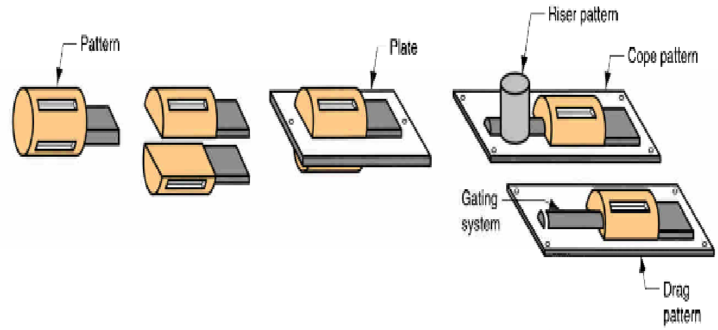


Figure 6 Different types of the pattern [7]

The binders are mixed with the sand to enhance the properties of the sand. According to the binders, foundry sand is divided into [7]:

- o Greensand (Clay sand);
- o Water glass sand (Sodium silicate sand);
- o Resin sand (Phenolic or Furan).

II. Investment casting

Investment casting is another form of expendable casting process which uses an expendable pattern unlike sand casting, which utilizes a permanent pattern. It is also called as lost wax casting. It is one of the easiest methods of casting. In this process, small parts such as jewelry can be produced.

Essentially, the process involves the following steps [9] (Figure 7):

1. Making a wax pattern that is expendable;
2. Investing or encasing the pattern in a suitable refractory material that can withstand high heat and reproduce every detail of the pattern in the form of the mold;
3. Burning out the pattern leaving a negative mold inside the investment material;
4. Casting by filling the mold with metal;
5. Recovering the casting by breaking the mold.

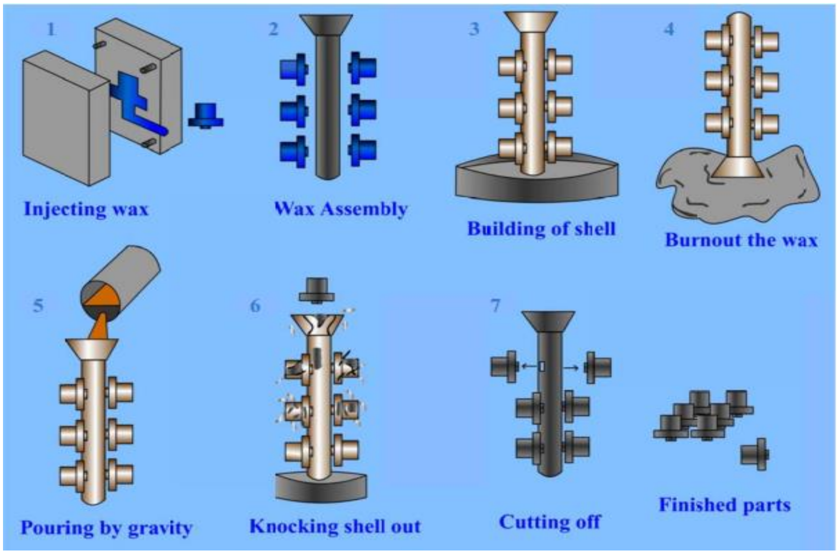


Figure 7 Steps in investment casting [9]

Because of the complexity of the process, most complicated shapes can be formed. The basic material used for this process comprises of paraffin, a mixture of Cristobalite [10].

III. **Shell molding**

Shell mold casting or shell molding is a casting process like sand casting. The difference between the two processes is that a more fine-grained sand is used compared to the sand casting process. It uses a thin hardened shell of sand and a thermosetting resin binder. Some of the typical parts that can be manufactured using this process include cylinder heads, gears, bushings, connecting rods, camshafts and valve bodies.

The various steps in shell mold casting are (Figure 8):

1. A match-plate or cope and drag metal pattern is heated and placed over a box containing sand mixed with thermosetting resin;
2. The box is inverted so that sand and resin fall onto the hot pattern, causing a layer of the mixture to partially cure on the surface to form a hard shell;
3. The box is repositioned so that loose uncured particles drop away;
4. Sand shell is heated in an oven for several minutes to complete curing;
5. Two halves of the shell molds are assembled together supported by sand or metal shot in a box and pouring is accomplished;

6. The final casting is removed with the help of a sprue.

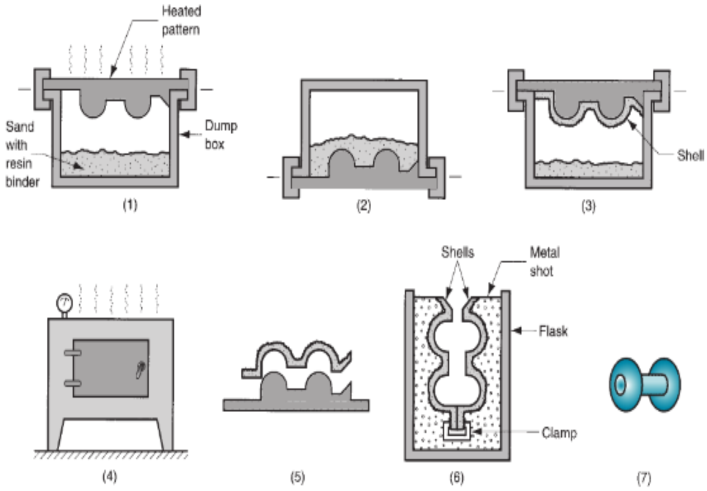


Figure 8 Steps in shell molding [8]

IV. Lost foam casting process

The development of the investment casting process led to the invention of the lost-foam casting process. In this process, the foam is used instead of wax. It uses an Expanded Polystyrene (EPS) foam pattern that is expendable [11].

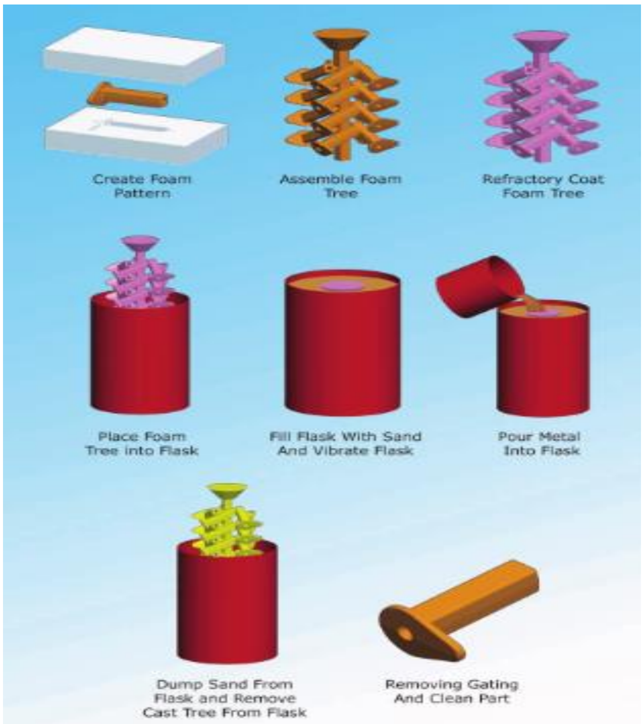


Figure 9 Steps in Lost-Foam casting [11]

Steps in Lost foam casting process (Figure 9):

1. The first step in the lost foam casting process is to create a foam pattern;
2. After creating a multiple foam pattern, an assembly of the foam is done to create a tree;
3. Then, the refractory coat (EPS) is applied to the assembled tree;
4. The foam tree is placed inside a flask and then filled with sand and vibrated;
5. The molten metal is poured into the flask;
6. The sand is dumped to remove the tree from a flask;
7. Finally, the gating is removed, and the part is cleaned.

B. Permanent mold casting

Permanent mold casting is a metal casting process that uses reusable molds that are mostly made of metals. The most common processes use gravity to fill the mold, although gas or vacuum can also be used.

Steps in permanent mold casting process (Figure 10)**:**

1. The mold used for casting is preheated and coated;
2. After the die is closed, molten metal is poured into the mold;
3. The casting gets solidified inside the mold and is removed by moving the movable die;
4. The casting is then cooled with the help of a cooling agent, for example, water.

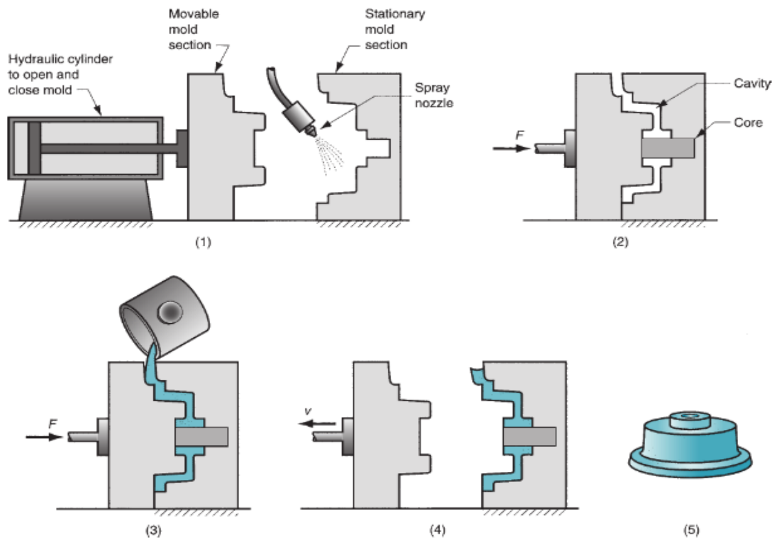


Figure 10 Permanent Mold casting process [8]

The most common types of permanent mold casting process comprising:

I. Centrifugal casting;
II. Slush casting;
III. Die-casting.

I. Centrifugal Casting

Centrifugal casting or roto-casting is a casting technique that is typically used to cast thin-walled cylinders [7]. In this process, the mold is rotated at a high speed that creates a centrifugal force and distributes the molten metal to the outer regions of the die cavity. It is divided into three types, namely:

- **True centrifugal casting** (Figure 11): The molten metal is poured into the rotating mold to produce a tubular part. The mold rotation occurs after the pouring the molten metal.
- **Semi-centrifugal casting**: The centrifugal force is used to produce solid castings, unlike true centrifugal casting. molds are designed with risers at the center to supply the feed metal.
- **Centrifuge casting**: The mold is designed with part cavities located away from the axis of rotation so that molten metal poured into the mold is distributed to these cavities by centrifugal force.

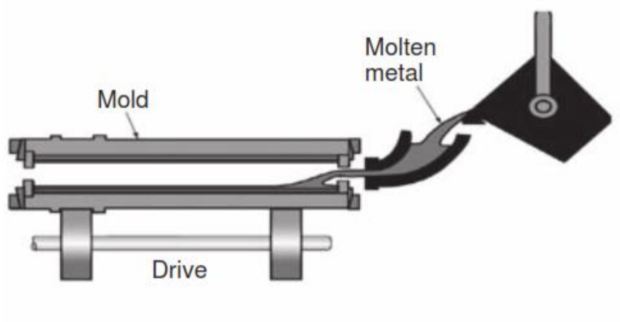


Figure 11 Centrifugal casting process [12]

II. Slush casting

Slush casting is a variation of the permanent mold process, aimed at producing the hollow casting. The principle behind this technique is to perform only partial solidification to obtain a thin geometry while the rest of the molten metal is disposed [8]. Alloys of low melting point like Zinc are cast with this process. The parts obtained has a good aesthetic look, although a lower strength compared to other casting processes.

III. Die casting

Die casting is the most growing technique in the global economy of casting production. It follows the principle of the permanent mold casting processes, where the differences are the use of external pressure to fill up the mold and the ability to cast parts of different melting points through the variations of the die casting technique. The pressure is maintained throughout the solidification process to produce thick castings.

The next section discusses in detail, the die casting process. The variations of the die casting process, the melting practice, and principles behind all the variants are detailed next.

2.1.3 Die castings and its variants

Die casting is a manufacturing process that produces metal parts of virtually all designs by forcing molten metal under high pressure into a die cavity [13]. Some of the highlighted features of the die casting process include:

- The metal die casting process has a short cycle time compared to sand casting or investment casting;
- The metal flow is faster in die casting due to the existence of external force;
- The mold in die casting is not as thin as those used in sand casting or investment casting processes.

The die casting process is used to produce parts made of various non-ferrous metals such as Brass, Zinc, Aluminum, and Magnesium. It can produce complex and detailed shapes.

The different types of die casting technologies are pressure die casting, gravity die casting and vacuum die casting.

A. Pressure die casting

Pressure die casting uses an external pressure with the help of a piston to distribute the molten metal across the mold. Thus, this process is faster. According to the pressure applied to the molten metal, it can be categorized into two groups, namely:

i. High Pressure die casting;
ii. Low pressure die casting.

i. High pressure die casting

High pressure die-casting is the most widely implemented technology in many industries. In this case, the molten metal is injected at high speed and pressure and a temperature of approximately 700°C. This process enables to produce a high volume of parts along with very good tolerances and finish [13].

Some factors must be considered to utilize this process. The factors include the recommended pressure that can be applied, the die heating temperature, weight of the part and suitable metal to inject. The most commonly used materials in this technology are Zinc and Aluminum.

ii. Low pressure die casting

The casting technology is also widely used by many industries. The surface finish of this process is mostly good. Here, the molten metal is injected at low pressure.

This process is used to produce small quantities. One of the main advantages of using this process is that the casting can be heat treated. It uses a pressure range between 2 and 15 psi.

B. Gravity die casting

Gravity die-casting is one of the processes adopted by many industries to reduce the production cost. It is used for both medium and high-volume production. Depending on the industry and its application, either manual or fully-automated system can be used.

Gravity die-casting depends on gravity for the molten metal to fill the mold unlike in pressure die casting, where an external force is applied to the molten metal. This process is also suitable for non-ferrous alloys such as Copper, Aluminum, and Zinc Alloys.

Steps in gravity die casting**:**

- The mold must be heated and sprayed with lubricant and then closed;
- The molten metal is then poured into the mold and then allowed to cool;
- After cooling, the die is opened to take out the parts;
- At last, the process is repeated.

C. Vacuum die casting

Vacuum die casting was developed as an advancement of pressure die casting. This process was developed mainly to reduce the porosity problem that occurs during pressure die casting.

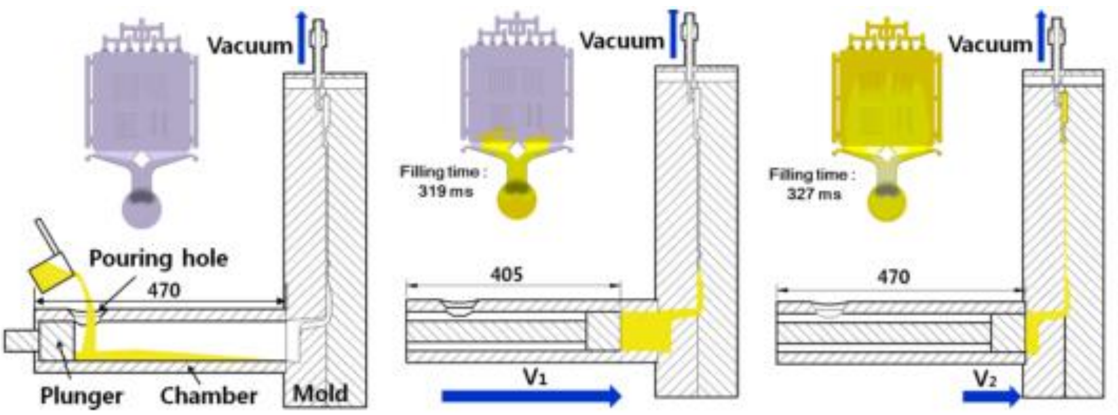


Figure 12 Vacuum die casting process [14]

The technology consists of using a steel die in an air-tight bell housing (Figure 12). The molten metal enters the die due to the pressure difference between the outlet top and sprue. In order to differentiate the pressure, the vacuum is varied. Since the process is complex, a proper control system must be employed.

2.1.3.1 Cold chamber injection process

Cold chamber die-casting is a permanent mold casting process [7]. Usually, large robust machines are used, exerting a high clamping force to hold both the die halves due to the presence of high pressure during the manufacturing process.

Cold chamber die-casting can be used to manufacture alloys with a high melting point such as Aluminum, Brass, Copper, and Aluminum-Zinc. It uses high pressure in the range of 20 MPa to 350 MPa to inject the molten metal into the die. The main advantage of the cold chamber process is that parts of intricate and thin walls and superior mechanical properties can be obtained. In this process, the molten metal is poured for each short, thus making the production more time-consuming.

Steps in cold chamber die casting process (Figure 13)**:**

1. At first, when the die is closed, the ram is withdrawn and then the molten metal is poured into the chamber;
2. With high pressure, the ram pushes the molten metal into the die and the pressure is maintained;
3. Finally, the ram is withdrawn, and the part is ejected from the die.

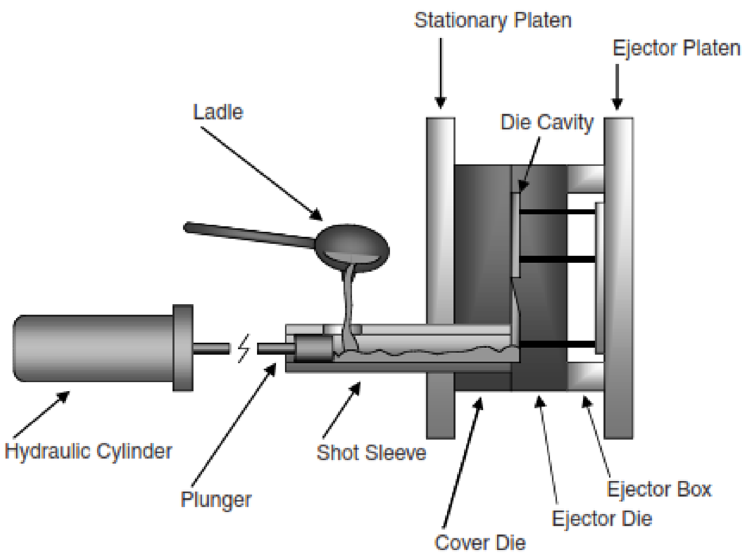


Figure 13 Cold chamber injection process [15]

2.1.3.2 Hot chamber injection process

Hot chamber casting is another technology where the molten metal is stored in a container connected to the die unlike the cold chamber process, which requires an injection of molten metal for every shot [7].

Since it is a quick process, the production is high compared to the cold chamber process. But this process is limited to low melting point alloys such as Zinc, Tin, Lead, and

Magnesium. It differs from a cold chamber process in the sense that the die is pre-heated before the molten metal is injected.

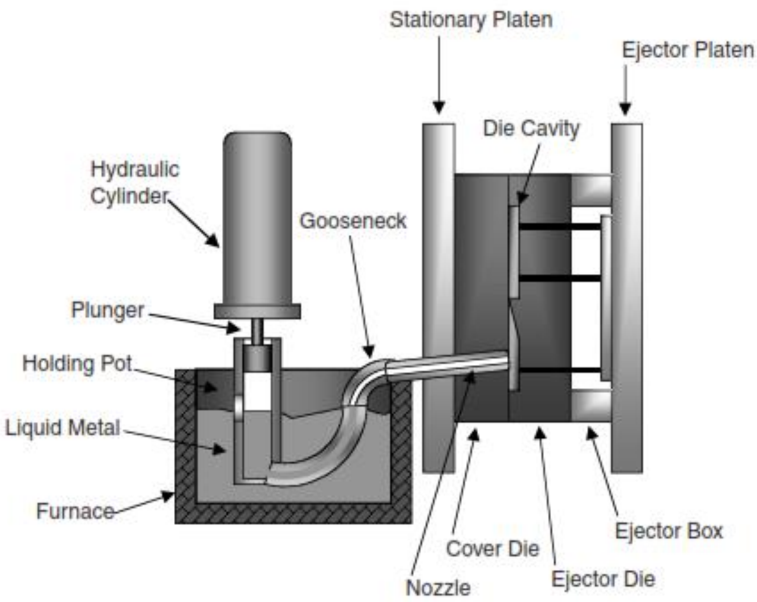


Figure 14 Hot chamber injection process [15]

Steps in the hot chamber die casting process (Figure 14)**:**

1. Initially, the die is closed, and the cylinder connected to the die is filled with molten metal;
2. The plunger or piston in the cylinder pushes the molten metal through the passage and nozzle into the die;
3. After this molten metal solidifies in the die and the plunger retracts with the rest of the molten metal;
4. The ejector pins push the casting part out of the ejector die and then cooled with water.

2.1.3.3 Main parameters and their control

The quality of the casting depends on the process parameters. Each of the parameter influences on the type of defects occurring. For example, the increase in the applied pressure enhances the mechanical properties of the resulting alloy and reduces porosities [16]. On the other hand, there are certain injection parameters that need to be controlled as well. For example, higher values of gate velocity and intensification pressure reduce porosity and increase the tensile properties [17].

The enhanced mechanical properties can be obtained in the case when the pouring temperature and die temperature are kept high [18]. If the temperature of the molten metal drops drastically during mold filling, the pressure rises and the flow velocity decreases. This leads to a defect called cold shut [19].

A test was conducted by Lopez and Faura [20] to analyze the behavior of molten metal in the injection chamber in HPDC. The test suggested that there is a critical plunger speed above which there is air-entrapment due to a wall-jet formed along the chamber ceiling.

After the plunger velocity, another important parameter is the time of filling the mold cavity. When the fill time is slow, the cavity does not allow the gases and vapors to escape the mold, thus degrading the quality of the mold [21].

2.1.3.4 Furnaces

A furnace is an equipment to melt metals for casting or for heating materials for a change of shape or for a change of properties. The selection of the melting furnace is a principal factor in a foundry process. Each furnace type has its own characteristics and applications. Selecting the appropriate furnace depends on the type of metal that is used for casting. The furnace is a crucial element in a foundry to eliminate the casting defects. The melting furnace used in non-ferrous melting depends on foundry size. The reason is that, often, these foundries use a different type of alloys. Since the foundries have limited capacity, the crucible furnace is the most widely used type of furnace. Typically for non-ferrous alloys, induction, hearth, and shaft furnaces are commonly used by the industries [22].

A. Crucible furnace

To melt non-ferrous alloys in small quantities, the crucible furnace is the most cost-effective method. It is coated with refractory walls, which allows reducing the heat loss to the outside. The life and energy efficiency of this type of furnace is low due to heat loss due to radiation.

Crucibles are pots made of fireclay mixed with coke dust or graphite, very densely compacted, carefully dried and fired at elevated temperature.

The crucible is tilted manually with a crane or automatically to pour the molten metal into the mold [23].

Melting Aluminum in a crucible furnace needs proper control because metal contamination usually occurs. Hence, a coating should be applied to the sides of the pot to avoid contamination. Also, fluxes like Aluminum Chloride are mixed along with the alloy to reduce the scum and dross formation [24].

B. Induction furnace

Induction furnaces are used to melt both ferrous and non-ferrous alloys. The induction furnace works with the basic principle of utilizing a strong magnetic field by passing an electric current through a coil wrapped around the furnace. The electric resistance of the metal produces heat and, thus, melts the metal. It is incorporated with various thermostats and flow-meters.

The induction melting has some restrictions on the type of metal that can be melted because it is sensitive to the quality of charge materials [25]. However, there have been many technological advancements in the past years that lead to increasing in its popularity in non-ferrous industries.

A major problem in furnace melting is the melt loss. This problem is reduced in the induction furnace by introducing combustion air into the furnace and when molten metal is stirred [26]. There are two types of induction furnaces deployed in the industry, namely, the coreless induction furnace and the channel induction furnace.

C. Rotary furnace

Rotary furnaces are commonly used by small-scale industries as an alternative to induction furnace. Recent advancements observed in the furnace are the ability to tilt and complete automation [23]. Tilting minimizes the time to produce melt by reducing some steps. The most recent advancement in rotary furnace technology is the development of Continuous Process Rotary Furnace (CPRMF). The main advantage is that the scrap can be charged continuously while the hot metal is tapped in batches [27].

D. Hearth furnace

The hearth furnace is also called as a reverberatory furnace. The molten metal is heated with the help of burners mounted either on the roof or sidewall of the furnace. The typical capacity of a reverberatory furnace between 1 to 75000 tons, which is the reason why it is used in most non-ferrous industries [23].There are two types of furnaces depending on whether the sows, ingots and revert materials are preheated. A dry hearth reverberatory furnace pre-heats the ingots, sows and revert materials whereas the side-well reverberatory furnace does not follow this principle.

2.1.4 Molds for metal injection processes

As there are varied demands from different customers, the type of the die is an important aspect of the casting industry [28]. The choice of the die is usually determined by the following:

- Size of casting part;
- The volume of parts required;
- Requirements for family sets of parts;
- The desirability of core slides;
- Requirements for cast-in inserts.

The several types of dies are as follows [28]:

I. Prototyping

Prototyping dies are those used for research purpose designed according to customer demands to produce a small number of castings. Since this is a prototyping die, it cannot yield castings with precise characteristics. Hence, certain prototyping strategies are used such as gravity casting machining from previously die-cast parts and techniques like stereolithography.

II. Rapid tool dies

Rapid tooled dies are used for shorter lead time requirements, instead of using conventional methods of rough machining, heat treating and finish machining. Some of the common tooling methods are Laser Engineered Net Shaping (LENS), Electron Beam Melting (EBM), Rapid Solidification Process (RSP), Selective Laser Sintering (SLS), and Direct Metal Deposition (DMD). The tooling method can be decided according to the production volume requirements.

III. Trim die

Trim dies are the type of dies with an option to trim the runners, overflows, and flash from the casting. Depending on the application, they can be constructed with a simple open and close die or include multiple slides.

IV. Production dies

Production dies are the most widely used type of die. They range from the single cavity die (Figure 15) to the multiple-cavity die (Figure 16). The cavities in these dies are made of the high-quality tool die with some amount of machining.

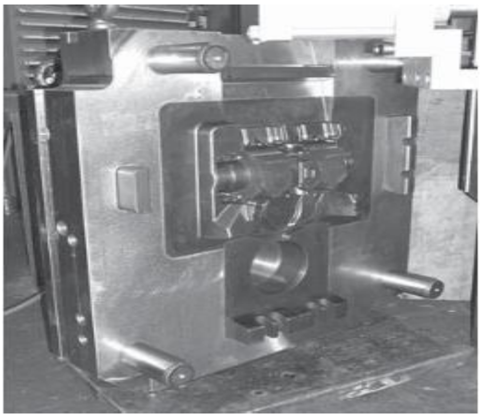


Figure 15 Single Cavity die[28]

Figure 16 Multiple cavities die[28]

V. Unit dies

A unit die is a tool die that has a standardized main die frame and replaceable cavity units. There are two types of unit dies, namely, single and double unitholders. These dies are mostly used for smaller parts or family of parts with no slides or a minimum number of slides (Figure 17).

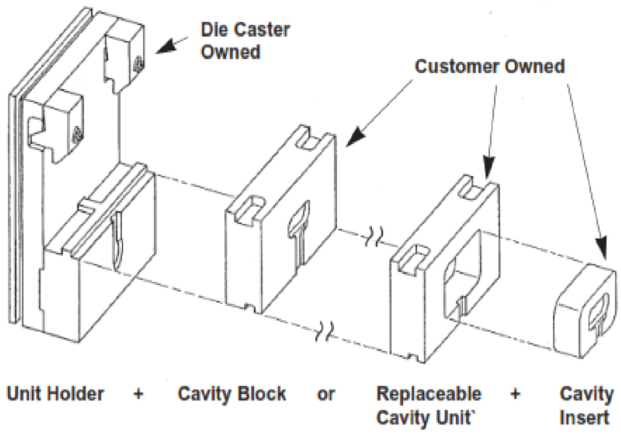


Figure 17 Unit die with options for die construction [28]

2.1.5 Parts design rules in die casting

Die casting depends on certain design rules in order to obtain a quality casting. Swain [29] created some guidelines that need to be followed, which include:

- Identify the possibility of incorporating several functions into one die casting. For example, it should be important to reduce machining;
- Before the design and construction of the die begins, the designer should finalize the design of the die casted product and the producibility because, after machining, the die undergoes heat treatment for hardening;
- The designer must consult die caster about the location of the ejector pin as early as possible in the product design stage;
- Another key factor is to avoid section changes, sharp corners and walls at an acute angle, as these lead to discontinuities of metal flow and surface irregularities;
- Blind recesses must be provided in the die to form bosses. This is because there is a possibility of developing subsurface porosities and they also cause the drill to wander and taps to break in secondary machining.

According to NADCA standards [28], it is important to know the customer's design requirements as they directly affect the size, type, features, and cost of required tooling. The requirements related to tooling decisions include the number of cavities, number of cores, weight of the die, machining, finishing requirements, polishing, and plating.

In 1987, research was conducted by Kandeil [30] on the design parameters and machine performance to enhance the quality of die casting. The review produced the following recommendations:

- To allow a smooth transition in the flow direction, the runner sprue must be properly designed;
- For straight sections and bends of the main runner, it is recommended to allow a reduction of 10% and 10-30% respectively in the cross-sectional area;

- For an enhanced flow pattern, a single-tapered runner is more advantageous than twin-tapered runners;
- Shock absorbers must be placed tangentially to runners;
- The runner surface must be polished properly to reduce pressure losses due to friction;
- The total gate area should not be less than 40% of the area of the nozzle to avoid excessive speed of molten metal at the gate;
- The true gate speed is an important parameter which is given by the relation

Equation 1 Formula for calculating true gate speed

$$True\ gate\ speed = \sqrt{(Runner\ speed)^2 + (Gate\ speed)\hat{}2}$$

- Total vent cross-sectional areas of up to 20% of gate area are recommended.

The parting line is another important parameter while designing a die [31]. It is the perimeter on the casting, which is the separation point of two halves of the casting die. It implies which half is the cover die half and which is the ejector half. It also influences the tolerance of the die-cast part.

A quick guide to tolerancing dimensions is shown in Figure 18.

QUICK GUIDE TO COORDINATE DIMENSIONING

Die Casting Alloy:	Aluminum	Magnesium	Zinc/ZA-8
WALL THICKNESSES			
Nominal wall thicknesses that can be die cast are heavily dependent on part geometry. With small castings, wall thicknesses of 0.030 in. (.762 mm) may be			
LINEAR DIMENSION TOLERANCES **Length of Dimension** in same die half			
Basic Tolerance up to 1" (25.4 mm)	±0.002 (±0.05 mm)	±0.002 (±0.05 mm)	±0.002© (±0.05 mm)
Additional Tolerance for each additional inch over 1" (25.4 mm)	±0.001 (±0.025 mm)	±0.001 (±0.025 mm)	±0.001© (±0.025 mm)
PARTING LINE TOLERANCES—added to Linear Tolerances **Projected Area of Die Casting: inches²** (cm²)—Tolerances are "plus" values only			
up to 10 in² (64.5 cm²)	+0.0035 (+0.089 mm)	+0.0035 (+0.089 mm)	+0.003 (+0.076 mm)
11 in² to 20 in² (71.0 cm2 to 129.0 cm2)	+0.004 (+0.102 mm)	+0.004 (+0.102 mm)	+0.0035 (+0.089 mm)
21 in² to 50 in² (135.5 cm² to 322.6 cm²)	+0.005 (+0.153 mm)	+0.005 (+0.153 mm)	+0.004 (+0.102 mm)
51 in² to 100 in² (329.0 cm² to 645.2 cm²)	+0.008 (+0.203 mm)	+0.008 (+0.203 mm)	+0.006 (+0.153 mm)
101 in² to 200 in² (651.6 cm² to 1290.3 cm²)	+0.012 (+0.305 mm)	+0.012 (+0.305 mm)	+0.008 (+0.203 mm)
201 in² to 300 in² (1296.8 cm² to 1935.5 cm²)	+0016 (+0.406 mm)	+0016 (+0.406 mm)	+0.012 (+0.305 mm)
For projected area of die casting over 300 in2 (1935.5 cm2), **consult MES.**			
MOVING DIE COMPONENT TOLERANCES—added to Linear Tolerances **Projected Area of Die Casting: inches2** (cm2)—Tolerances are "plus" values only			
up to 10 in² (64.5 cm²)	+0.006 (+.152 mm)	+0.005 (+.127 mm)	+0.005 (+0.127 mm)
11 in² to 20 in² (71.0 cm² to 129.0 cm²)	+0.010 (+0.254 mm)	+0.007 (+.178 mm)	+0.007 (+0.178 mm)
21 in² to 50 in² (135.5 cm² to 322.6 cm²)	+0.014 (+0.356 mm)	+0.010 (+0.254 mm)	+0.010 (+0.254 mm)
51 in² to 100 in² (329.0 cm² to 645.2 cm²)	+0.018 (+0.457 mm)	+0.014 (+0.356 mm)	+0.014 (+0.356 mm)
101 in² to 200 in² (651.6 cm² to 1290.3 cm²)	+0.024 (+0.61 mm)	+0.019 (+0.483 mm)	+0.019 (+0.483 mm)
201 in² to 300 in² (1296.8 cm² to 1935.5 cm²)	+0.030 (+0.762 mm)	+0.024 (+0.61 mm)	+0.024 (+0.61 mm)
For projected area of a die casting over 300 in2 (1935.5 cm2), **consult MES.**			
FLATNESS TOLERANCES: **inches** (mm) **Maximum Dimension of Die Cast Surface**			
Up to 3.00 in. (76.20 mm)	0.005 (0.13 mm)	0.005 (0.13 mm)	0.005 (0.13 mm)
Additional tolerance, in. (mm) for each additional in. (mm)	0.002 (0.05 mm)	0.002 (0.05 mm)	0.002 (0.05 mm)

Figure 18 Co-ordinate dimensioning according to the MES guide [31]

2.2 Defects in castings

Casting is a process which carries the risk of failure occurrence during all the process of accomplishment of finished products. Mostly, these casting defects occur due to the process parameters.

Defects are needed to be controlled to reduce the production losses. Thus, casting defect analysis must be carried out because the process enables to finding the root causes of the occurrence and hence, rectifying it.

2.2.1 Atlas of defects in die casting

Conventional die casting defects are classified into three main categories [32]:

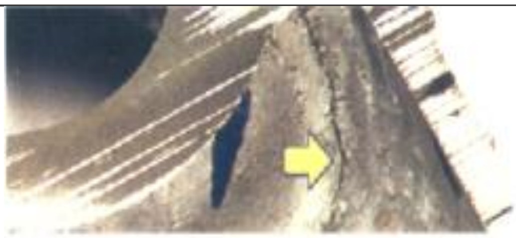
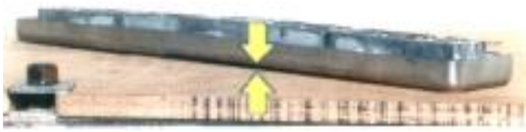
- **Surface defects**: Surface defects are usually visible on the exterior of the component are called surface defects. Components are discarded where aesthetics are important. A common type of surface defects are cold shuts, surface contamination, cracks, drags, flash, laminations, short shot, and sinks.
- **Internal defects:** Internal defects may occur below the surface of the component. The detection of this type of defects is difficult. Inclusions and porosities are the most commonly occurring internal defects.
- **Dimensional defects:** Dimensional defects are related to geometric dimensions. These defects do not usually occur at the beginning of production as they are progressive over time. Some of the types of dimensional defects are sharp corners, erosion, and warpage.

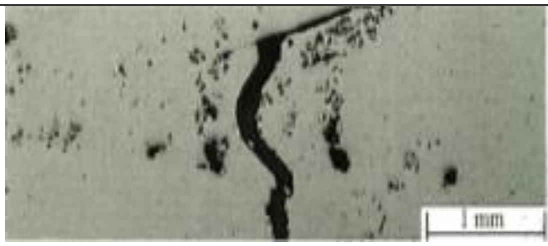
Table 1 shows the description of the type of defects with a depiction:

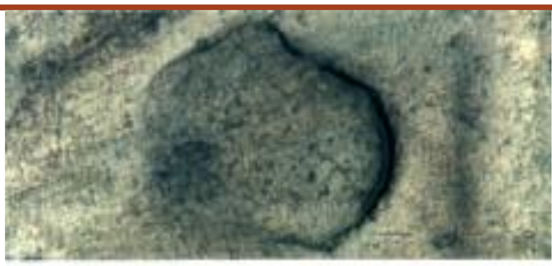
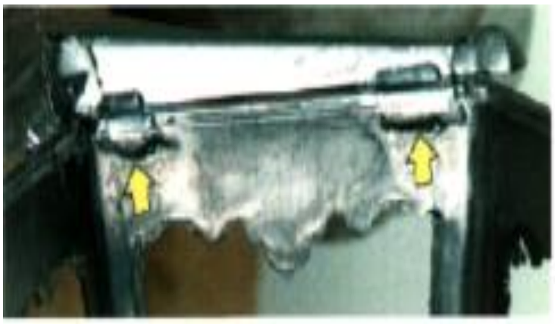
Table 1 Aluminium High-Pressure Die Casting Defects (Refer Figure 72 in annex)

S. No	DESCRIPTION	IMAGE
1	**Short fill**- The metal is frozen before the cavity is filled or by insufficient metal being ladled.	
2	**Cold shut**- The metal is frozen when two metal fronts join.	

3	**Scaling**- Layers of metal and oxides on the part.	
4	**Blister**- Compressed gases which are trapped in the cavity get expanded.	
5	**Flash-** The metal projections on the casting surface due to high pressure.	
6	**Cold flakes**- Molten metal that gets cooled in a short-sleeve that gets injected into the cavity.	
7	**Shot lube stain**- Defect that occurs when excessive shot lube is used.	
8	**Air porosity**- Defect that occurs due to trapped gases.	

9	**Drag marks**- Marks that are formed during the ejection due to the insufficient draft.	
10	**Hot tearing/cracking**- Cracks that occur due to metal shrinkage during solidification.	
11	**Hot shortness**- Defect that occurs in points of high stress at elevated temperature.	
12	**Sink**- Defect that occurs when the shrinkage cavity is near the casting surface.	
13	**Exploded metal**- The trapped gases in the casting burst out on the metal surface before solidifying completely and ejected.	
14	**Warpage**- Deformation occurring after ejection when the metal cools down to room temperature.	
15	**Soldering**- Aluminium tears away from casting due to chemical attack against the die steel.	

16	**Shrinkage porosity**- Reduction in metal volume that occurs during shrinkage.	
17	**Heat checking**- Defect that occurs when the surface of the tool expands and collapses continuously.	
18	**Leaker**- The casting splits due to distinct reasons.	
19	**Discolored surface**- Oxide films or residues or excess die lube discolors the surface.	
20	**Break out**- Metal flakes which get caught in the gate during cavity fill can break out unevenly.	
21	**Inclusions**- Dirty or contaminated metal adheres to the casting.	

22	**Ejector damage**- Excessive pressure on the ejector by ejector pin damages the casting.	
23	**Erosion/Cavitation**- Turbulence occurring on low-pressure regions forms voids that collapse at the die surface.	
24	**Cracked casting**- Crack that occurs due to mechanical damage when the die is opened or when the casting is ejected.	

2.2.2 Main root-causes

Casting is a process that carries the risk of failure occurrence during all the process of accomplishment of the finished product. Mostly, these casting defects are concerned with different process parameters. So, in order to reduce failures, different process parameters must be controlled. Prior to implementing any solution, the die caster must be aware of the types of defects, the effect of each and every parameter and then identify the root causes of the defects [23].

Porosity in castings is the most frequently occurring defect. It can be of two forms, namely gas porosity and shrinkage porosity. Gas porosity occurs due to:

- **Gas held in molten metal during treatment:** Hydrogen gas is the main source of gas porosity. Hydrogen pick-up can be found from the use of damp refractories in furnaces or ladles. Another source of hydrogen comes from the running system due to reactions with mold.

- **Poor parameter condition during filling:** Plunger velocity is an important parameter in filling. When the plunger velocity is too high, surface turbulence is generated. This does not allow the gases to escape, thus creating a scrambled mass of metal and air is held by the oxide film [33].

Another common defect that occurs in castings is crack. These occur when the molten metal pulls itself apart while cooling in the mold. Prolonged cracks until the end of solidification lead to hot tear defect. It occurs in metals that have a wide freezing range since the isolated regions of the liquid become subjected to thermal stresses during cooling [34].

According to Imane [35], the microstructure changes depending on different pressure and material temperature. At high pressure, the mechanical properties such as hardness, yield strength, and ultimate tensile strength are enhanced, whereas, at low pressure, the highest level of porosity is obtained. At high temperature, it is noted to have fewer porosities.

Surface defects such as cold flow, cold shut, no-fill, and miss-runs occur due to factors such as the wall thickness, fill time, flow pattern, die and metal temperature. A minimum of 1.5 mm of wall thickness must be present because it causes the molten metal flow to freeze and develop a cold flow. Fill time is another parameter causing surface defects. A high die temperature is needed in order to reduce the percentage of solidified metal in the metal stream [36].

In summary, the injection parameters, molten metal characteristics, die design and characteristics such as runner design, gate design, and sleeve features, lubrication parameters and cycle time are the main root causes that affect the quality of casting.

2.2.3 Usual solutions

The first step towards minimization of casting defects is to have a scrap reporting system. The scrap report must be categorized by at least one of the followings items[37]:

- By defect type;
- By part number;
- By die;
- By shift;
- By operator;
- By machine.

Defects cannot be improved without measurement. The most common method used for defect measurement is X-ray, machining or sawing.

Avinash [38] performed an industrial case study to reduce casting defects. The main tool used was the cause and effect or Ishikawa diagram, as it helps in determining the control factors that are most influential on the quality of casting.

Gas porosity is another common defect that occurs in casting. The use of vacuum-assisted casting is a common method that helps in eliminating the trapped gases during the process [39].

The simulation also plays an important role to analyze and solve defects. Mahipalsinh [40] used a software called SOFT CAST to reduce shrinkage defect. With the software, shrinkage defect can be identified, and optimum feeding design can be determined to reduce the shrinkage defect.

Table 2 shows the description of the solution of every defect:

Table 2 Defects and their solutions [37]

S.NO	DEFECT	SOLUTION
1	Crack	Adjust the die, plunger cooling and check to die spray
2	Shrinkage	Check the interval die cooling
3	Soldering	Polish the die surface and adjust the spray
4	No-fill	Maintain the temperature in the holding furnace between 640-680°C
5	Gas porosity	Clean the chill-vents and overflow surfaces
6	Blowholes	Adjust the intensification pressure and biscuit thickness
7	Inclusions	Clean the molten metal
8	Cold flow	Heat the die and the metal alloy before pouring
9	Scaling	Adjust the metal pressure and 1^{st} stage velocity
10	Sink	Focus on pressure and keep the die at the proper temperature and proper spray
11	Leaker	Focus on 2^{nd} stage velocity, die temperature and die spray
12	Short fill	Focus on pouring temperature and fill time
13	Blisters	Keep the first stage velocity as required and frequent inspection on the shot sleeve and die for damage
14	Flash	Focus on metal temperature and second stage velocity
15	Cold flakes	Check the composition of the alloy and die temperature
16	Shot lube stain	Focus on shot lubrication with an optimum level
17	Drag marks	Keep the optimum level of draft allowance and pre-heat the die
18	Hot shortness	Check the metal composition and ejection parameters
19	Warpage	The die design and gate design must be checked
20	Heat checking	Focus on-die temperature and die spray
21	Exploded metal	Keep the optimum level of first stage velocity and also check the die spray
22	Erosion / Cavitation	Check the runner and gate design and keep the optimum level of second stage velocity
23	Break out	Check for metal impurities and also a runner and gating system
24	Discolored surface	Check the ejection parameters and amount of plunger lubricant

2.3 Quality tools and evaluation

Quality is an important parameter that decides the satisfaction level of the customers [41]. Quality has two important concepts:

- The finished product must meet the specifications;
- Customer satisfaction depends on quality products and services.

A sound quality control system must be implemented in order to satisfy the aforementioned concepts. The objective of quality control (QC) is to improve the industry income by making the product more acceptable to customers, by providing long life, greater usefulness, versatility, aesthetics.

2.3.1 Definition of quality

Different people differently perceive quality. The dictionary meaning of quality is “the degree of excellence” [42].

B.Crosby [43]: Quality is conformance to requirements. The belief of Crosby is to “doing it right the first time”. The four major principles are:

- Quality is conformance to requirements;
- The management system is prevention;
- The performance standard is ‘zero defects’;
- The measurement system is the cost of non-conformance.

M.Juran [44]**:** Quality is fitness for use. He proposed the quality trilogy:

- Quality planning: Quality planning is the process of preparing to meet the company’s goals. Both internal and customers are determined, and their needs are determined;
- Quality control: Quality control is the process of meeting company goals during operations and statistical process control techniques are the primary tools of control;
- Quality improvement: Quality improvement is the process of breaking through to superior, unprecedented levels of performance.

W. Edwards Deming [45]**:** Good quality means a predictable degree of uniformity and dependability with a quality standard suited to the customer. Deming’s philosophy is based on fourteen principles.

American Society for Quality (ASQ) [42]**:** Quality denotes an excellence in goods and services, especially to the degree they conform to requirements and satisfy customers.

Armand V. Feigenbaum [42]**:** Total quality control is an effective system for integrating the quality development, quality maintenance and quality improvement efforts of the various groups in an organization, so as to enable production and services at the most economic levels, which allow full customer satisfaction.

2.3.2 Control quality tools

Dr. Kaoru Ishikawa [46] was the first quality guru who proposed seven basic tools to an assist an organization for problem-solving and process improvements. The seven quality control tools are:

I. Check sheets;
II. Histogram chart;
III. Pareto chart;
IV. Fishbone diagram;
V. Scatter diagram;
VI. Control chart;
VII. Stratification diagram.

I. Checksheet

Checksheet is a chart that depicts the frequency of events occurring during a process [46]. The main advantage of the check sheet is the ability to easily understand and depict the situation. There are three types of check sheets, namely defect location check sheet, tally check sheet, and defect-cause check sheet. Figure 19 shows an example of a check sheet.

OUTPUT CONTROL DOCUMENT CASTING, NUMBER: 220.351-2 MONITORED FROM 18/11 TO 22/11						
MOULD NUMBER	DAY	NUMBER OF NON-CONFORMING PRODUCTS (pcs)				
		Shift A	Σ	Shift B	Σ	Σ
1	Mon	xxxxxxxx	8	xxx	3	11
	Tue	xxxx	4	x	1	5
	Wed	xxxx	4		0	4
	Thu	xxx	3	xx	2	5
	Fri	xxxxx	5		0	5
Σ1			24		6	30
2	Mon	xxxxxx	6	xx	2	8
	Tue	xxxxxxx	7	xxx	3	10
	Wed	xxxxx	5	x	1	6
	Thu	xxxxxx	6	xx	2	8
	Fri	xxxxx	5	x	1	6
Σ2			29		9	38
3	Mon	xxxxxx	6	xx	2	8
	Tue	xxx	3		0	3
	Wed	xx	2	x	1	3
	Thu	xxxx	4	x	1	5
	Fri	xxx	3	x	1	4
Σ3			18		5	23
Total			71		20	91

Figure 19 Checksheet to solve casting defects in different shifts and on different days [47]

II. Histogram chart

The histogram is a tool to describe the sense of frequency distribution of observed values of a variable. It displays different measures of central tendency such as mean, mode and average. Figure 20 shows a visual representation of a histogram chart.

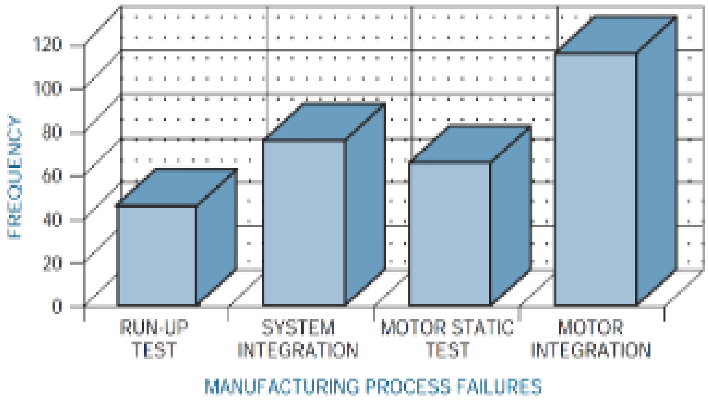


Figure 20 Frequency of defects in a manufacturing process [46]

III. Pareto chart

The Pareto chart is based on a principle that, 80% of effects come from 20% of causes. It is a special type of histogram that can be used to find and prioritize quality problems or situations of a case study. The aim of a Pareto chart is to determine the non-conformity in a data-set. Figure 21 shows an example of a Pareto chart.

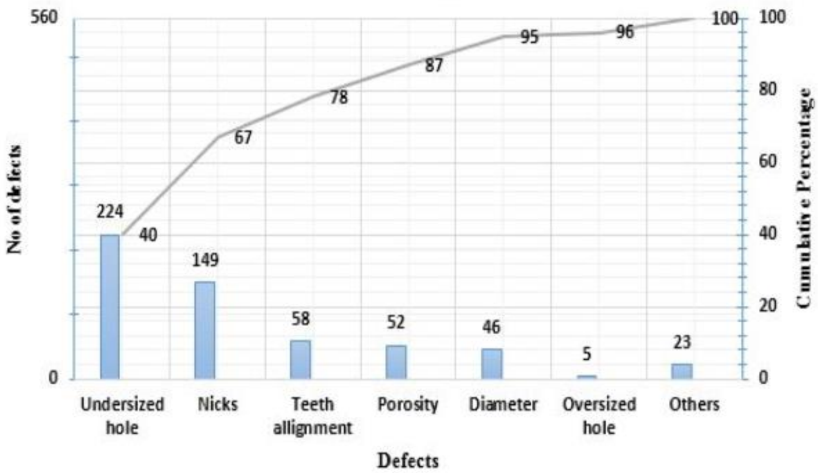


Figure 21 Pareto chart for the type of defect [48]

IV. Fishbone Diagram

The fishbone diagram, also called as the Ishikawa diagram is a tool used to determine the root cause of a problem. Hence, it is also termed as Cause and Effect Diagram. It is a problem-solving tool that systematically analyzes all potential causes that lead to a single effect. The defects are categorized by using six elements such as man, machine, method, materials, environment, and measurement (Figure 22).

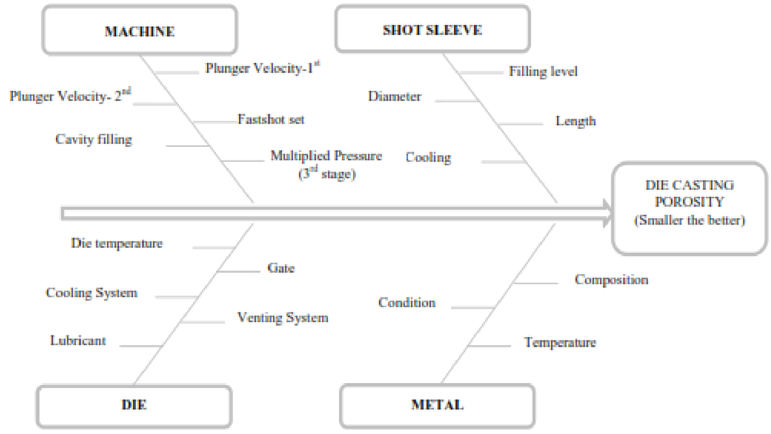


Figure 22 Representation of an Ishikawa diagram [46]

V. Scatter diagram

The scatter diagram is a powerful tool to detect and analyze the relationship between two different variables. It helps to understand if there is a relationship between the variables, and, if so, would it be a strong or weak relationship. The scatter diagram indicates one of the relationships such as positive, negative or no correlation (Figure 23).

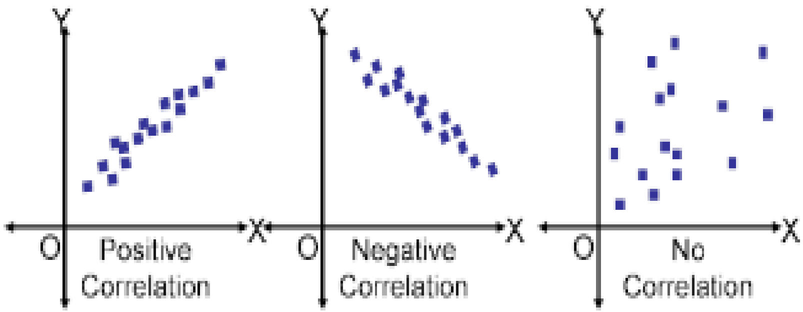


Figure 23 Scatter diagram example [46]

VI. Control chart

The control chart is the most sophisticated tool for quality management. It depicts the amount and nature of variation in a process over time. The nature of a variation, whether it is out of control or otherwise, is determined by Upper Control Limit (UCL) and Lower Control Limit (LCL) (Figure 24).

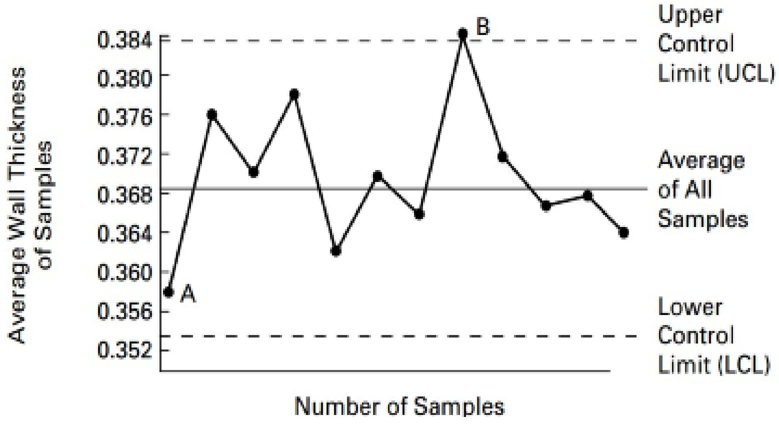


Figure 24 Representation of control chart [46]

VII. Stratification diagram

The stratification diagram, conversely known as a flowchart or run chart, is a visualization chart to depict a process. It enables to detect and analyze specific points or areas of a process that may have caused a problem. Since it is a flowchart, it is created with the help of general symbols, where each symbol has its own meaning. Figure 25 shows a pictorial representation of the gravity die-casting process.

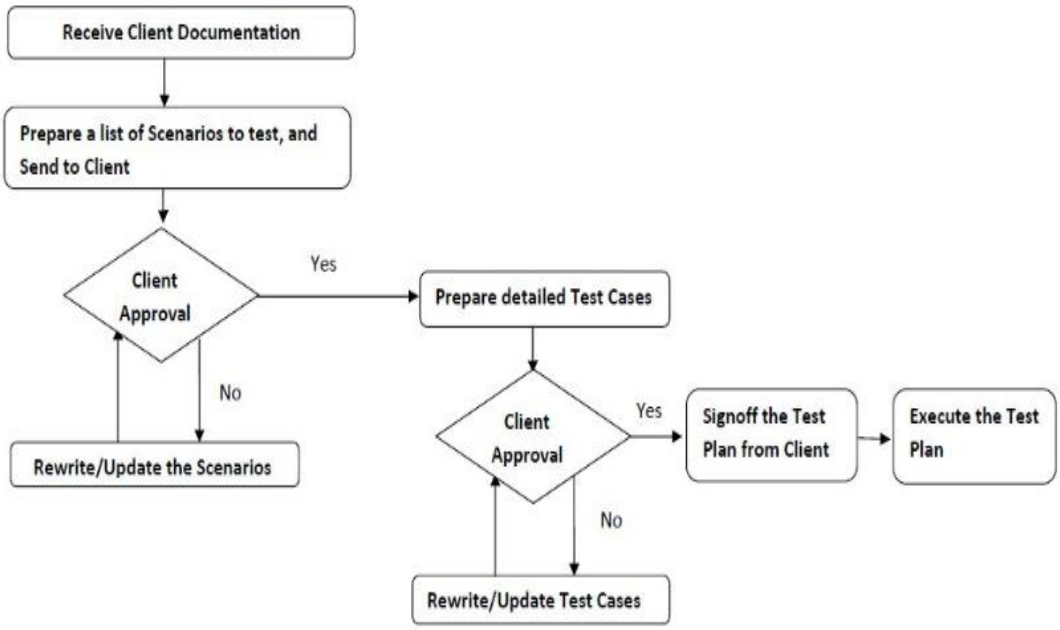


Figure 25 Flowchart of a review process [46]

2.4 Design of Experiments and Statistical Analysis

The Design of Experiments (DOE) is an important tool utilized by industries to control the process variables [49]. DOE has been proved to be a method to improve the product quality. By using DOE, it is possible to make improvement efforts to enhance a product's manufacturability, reliability, quality, and field performance.

DOE is often carried out in four phases:

- **Planning**: The planning phase involves defining the problem, objective, developing an experimental plan and inspecting statistical control;
- **Screening**: The screening phase, the number of variables affecting the product quality is determined and reduced to a vital few to improve;
- **Optimization**: The optimization phase involves determining the best values and developing into an appropriate matrix available in statistical software such as Minitab, SPSS or Microsoft excel;
- **Verification**: Verification is the final phase where the experiment is performed in order to obtain the optimization result.

There are different types of optimization methods available in Minitab, such as:

- Full factorial designs;
- Response surface designs;
- Mixture designs;
- Taguchi designs.

The selection of any type of optimization depends on the type of response and required design.

2.4.1 Taguchi methodology

Although different designs have different effects, it is imperative to find a design that is robust to environmental variations. Since the 1950s, Dr. Genichi Taguchi introduced several statistical tools for quality improvement [50].

Dean [51] suggested that the Taguchi approach can have benefits such as time and resource savings, determination of important factors, performance and cost reduction to have a high-quality solution.

According to Taguchi, there are three steps of quality design, namely:

- **System design**: System design involves the development of a system to function under an initial set of nominal conditions. It requires knowledge in science and engineering.
- **Parameter design**: Parameter design involves the selection of optimum levels for the controllable system parameters. Since the system is robust, it does not consider the noise factors that are accounting for variation.
- **Tolerance design**: The final phase is tolerance design, where the optimal parameters are narrowed to a specific tolerance range.

Figure 26 represents steps in Design of Experiments.

Figure 26 Flowchart for the Taguchi method (adapted from Phadke [52])

2.4.2 Selecting the variables to control

Anastasiou [53] performed a casting defect analysis using the Ishikawa diagram to scrutinize the parameters that affected the casting quality. The process parameters were divided into four main categories; relating to the die casting machine, shot sleeve parameters, die parameters and type of casting alloy. From these set of parameters, the holding furnace temperature, die temperature, piston velocity (first and second) and hydraulic pressure were considered as the most significant parameters affecting the quality.

On the other hand, Kulkarni Sanjay Kumar [54] studied the effect of different parameter settings on the porosity levels. The parameters were similar to the previous approach, but the only difference is the length at which the first stage velocity ends was considered as an important parameter.

2.4.3 Selecting the best matrix

After deciding the parameters and the interactions, the next step is to select the best matrix to carry out the experiments. In Taguchi design, response variables are measured for the selected combination of the parameter. Taguchi design, also known as an orthogonal array, is a fractional factorial matrix that ensures a balanced comparison of levels of any factor[49]. The following needs to be considered while choosing the design:

- Identify the number of control factors that are of interest;
- Identify the number of levels for each factor;
- Determine the number of runs you can perform;
- Determine the impact of other considerations (such as cost, time or facility availability) on the choice of design.

There are 5 different types of design namely:

- 2-level design;
- 3-level design;
- 4-level design;
- 5-level design;
- Mixed level design.

In the thesis of Guharaja [55], DOE was applied on a sand casting process, where nine parameters were selected. The orthogonal array was selected by calculating the Degree of Freedom (DOF), which is given as 26= (9*(3-1) +2(*2)), where nine parameters each at three levels and two interactions were used in the experiment. Hence, an L_{27} three orthogonal array is selected.

In another research conducted by Mahesh [56], an L_9 orthogonal array was chosen, since there were four parameters at three levels. Thus, the degree of freedom is an important parameter in selecting the orthogonal array.

2.4.4 Statistics applied to the DOE

The significance of each parameter must be checked after performing DOE. In order to determine the significance, an Analysis of Variance (ANOVA) should be performed.

Verran [57] performed a DOE analysis on an alloy of Al12Si1,3Cu which had a porosity problem and a high number of rejections. After performing DOE, ANOVA was conducted at 95% of confidence. As a result, the fast shot and upset pressure and also their interactions were determined to be the major factors for the amount of porosity.

Kumar [58] carried a die casting process optimization using the Taguchi approach and ANOVA in Minitab software to determine the parameters that affected porosity. The statistical analysis inferred that the injection pressure and pouring temperature were the main parameters that affected porosities.

In summary, statistics are important in a study to conclude the effect of different parameters affecting a product and make it easier to focus on the main causes and optimize.

2.5 Numerical Simulations

2.5.1 Significance of simulation

Simulation is an integral part of the foundry to achieve high-quality castings with optimal yield [59]. Casting simulation must be used when it can be economically justified for one of the followings:

- **Quality enhancement** by predicting and eliminating internal defects like porosities;
- **Yield improvement** by reducing the volume of feeders and gating channels per casting;
- **The rapid development** of a new casting by reducing the number of foundry trials.

Figure 27 shows the casting simulation based on different factors:

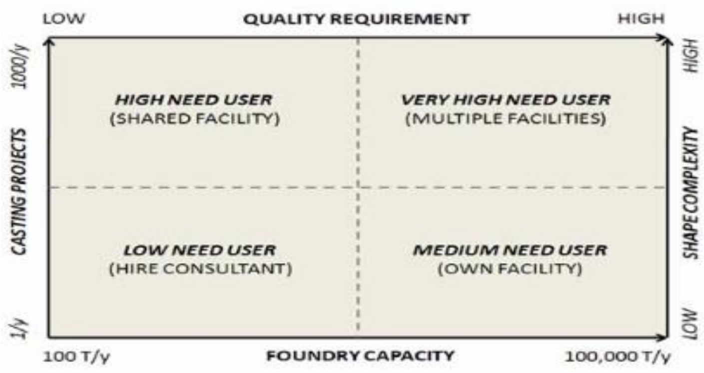


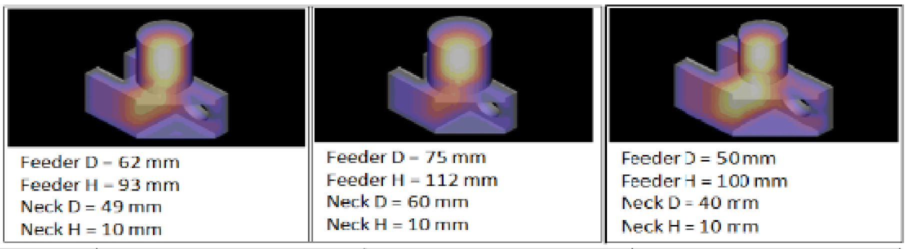
Figure 27 Types of casting simulation users based on different factors [59]

Rahul [60] used the Magmasoft FEM software to improve the quality of casting. This simulations studies enable to improve the quality of casting without carrying out the actual trials on the shop floor. Thus, with the study, the user can be able to optimize at the design phase and avoid complications at the shop floor.

2.5.2 Simulation optimization of die casting

Meng Bai [61] utilized simulation to optimize parameters such as pouring temperature, mold temperature, and second stage velocity to produce a good quality casting. Pro-E and Procast software the software used to check defects such as shrinkage porosities.

A review paper by Jadhao [62] performed an experiment to see the shrinkage effect based on runner design, with and without a feeder. He used three different design values of the feeder to determine the yield and used the result of the best design to obtain a reliable and high accuracy component (Figure 28).



	Designed Feeder	Larger Feeder	Smaller Feeder
Quality	Small shrinkage	No shrinkage	Major shrinkage
Yield	62%	48%	70%
Remark	Unacceptable	Acceptable	Suitable with sleeve

Figure 28 Comparison between the simulations with different dimensions for feeder [62]

Another important feature of simulation is the use of thermal analysis to determine the required solidification features. The solidification features include the effect of cooling rate on the formation of porosities [63].

Simulations enable to visualize the effect of gate design and process modifications [64]. It is also very useful in optimizing cavity filling and minimizing the defects formation. This allows to further increase the fatigue and tensile strength of a product.

THESIS DEVELOPMENT

3 THESIS DEVELOPMENT

3.1 Company presentation

Sonafi is an Aluminum alloy die-casting company founded in 1951, aimed at the automotive sector. Sonafi develops and manufactures components for various applications with complex geometry, with technologies such as die-casting, machining, shot blasting or vibration machining, machining, sub-component assembly, leak testing, and other anti-error and quality recording tests, according to the specifications agreed with the customer.

Figure 29 represents an image of the front office of Sonafi.

Figure 29 Image of the front office

It is located in the North of Portugal, within 10 km of space from Porto's airport. Sonafi stands for Sociedade Nacional de Fundição Injectada. The company consists of various departments such as process control, production department, quality control, human resource department, information technology division, maintenance department, logistics, finishing process department, and medical division.

Figure 30 Die casting machine

Figure 30 represents an image of the die casting cell.

The company employs around 55 employees spread across all the departments. Under the supervision of the employees, the production capacity of the company is high. In terms of production capabilities, the company has set-up four smelting furnaces and twenty-four die casting cells ranging from 320 T to 1400 T. The four furnaces are capable to produce 20 ton/day with different alloys, namely AlSi9Cu3, AlSi12Cu, and AlSi10Mg.

Figure 31 represents a robot used for removal of the casting from the cavity.

Figure 31 Robot for removal of casting from the cavity

Figure 32 Die heater

Figure 32 represents the die heater used as an equipment to heat the die

Similarly, the company has set-up machines and equipment for machining. For surface finishing, three shot blasting machines, one tumbling machine, and four vibration machines are utilized. To complete major machining jobs, thirty-four CNC machines, from different brands, such as Chiron vertical machine, Heller horizontal machine and Makin D horizontal machines are present. The company also has 17 transfer machines. Apart from all these machines, other equipment such as a washing machine, leak-proof test devices, assembly transfer machine, and test and control devices are used.

Figure 33 represents an image of the CNC machine.

Figure 33 CNC machines used by the company

3.2 Definition of the processes involved in HPDC process

The HPDC process is a relatively simple concept where a piston and cylinder arrangement pushes molten metal, in this case, aluminum into a die, and then apply high pressure. The molten aluminum is melted in a furnace and then transported to a holding furnace, which usually maintains the temperature between 650ºC and 700ºC.

The casting process cycle consists of five stages. The total cycle time is very short, in the range between 2 seconds to 1 minute.

Figure 34 shows the steps in the casting process.

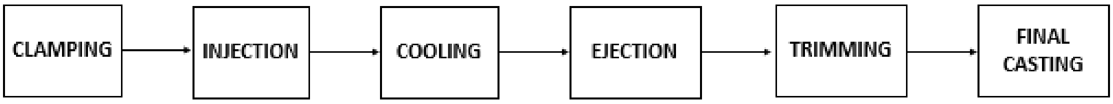


Figure 34 Casting process (Adapted from Rahimi [65])

Near the holding furnace, is attached, the shot chamber of the die casting machine. It consists of a cylinder, shot sleeve and plunger. The molten metal flows through an opening at the top of the shot-sleeve, which is pushed by the mechanism of the plunger, whose speed and force are monitored in a computer (Figure 35).

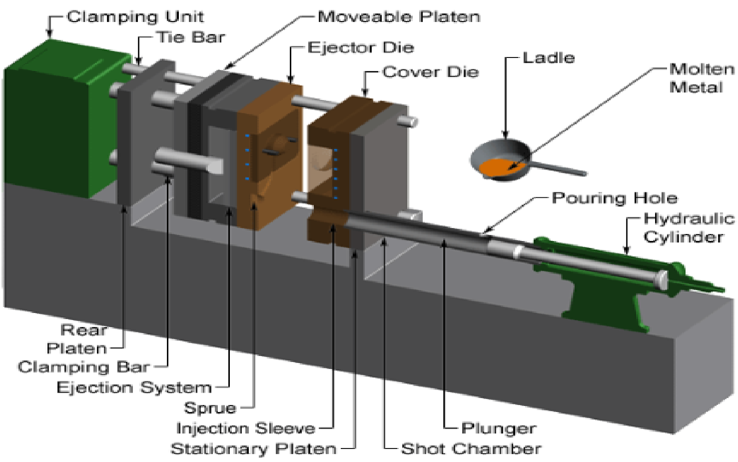


Figure 35 Cold chamber die casting machine in open position [65]

The plunger pushes the molten metal into a die. The die is usually made of two halves, of which one is movable and the other is fixed. The die is also maintained at a particular temperature to have a better flow of metal [66]. After the metal fills a part of the portion of the die, the locking mechanism of the die enables to form the desired casting shape, which is already machined inside the die (Figure 36). The part is then water cooled and transported to a CNC machine for machining.

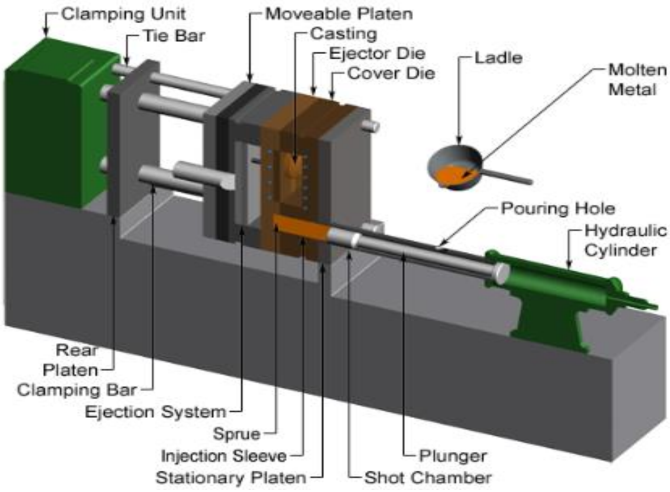


Figure 36 Cold chamber die casting machine in closed position [65]

After each shot is completed, the die is cooled for the next shot by the use of lubricant. The lubricant is generally a mix of oil and water, which is sprayed throughout the die with nozzles attached to a particular configuration. The die is then dried by blowing air throughout. The die heater allows the die to pre-heat to a particular set temperature. This cycle repeats again to continue the production.

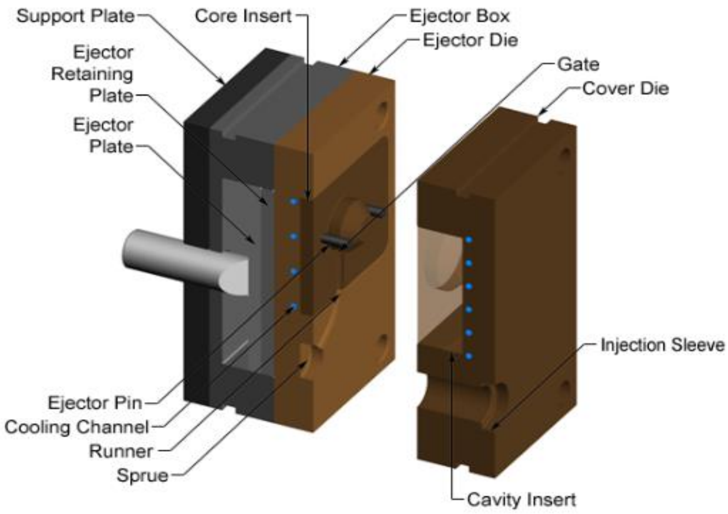


Figure 37 Cold chamber die assembly in open position [65]

The flow of molten metal into the part cavity requires several channels that are integrated into the die [65]. The molten metal flows into the die through the injection sleeve (Figure 37 and Figure 38). After entering the die, the molten metal flows through a series of runners and enters the cavities through the gates. Finally, there are cooling channels that allow water or oil to flow through the die and remove heat from the die.

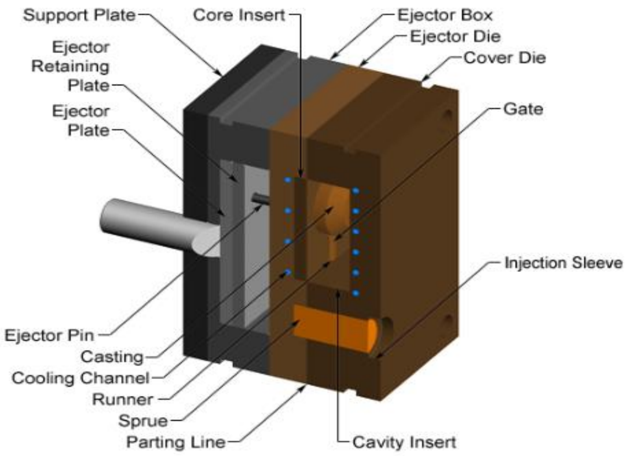


Figure 38 Cold chamber die assembly in a closed position [65]

Figure 39 Side image of the die casting machine

Figure 39 represents a side view of the die casting machine. It is a semi-automated machine, where the die casting process, injection of molten metal, lubrication, and water cooling of the castings, are automated operations. After water cooling of the casting, the runners and unnecessary projections are removed by the operator in a hydraulic press.

The two circular spots on the picture represent the lubrication system and manual controls of the die casting machine. The die is cooled by a high-pressure spray of water and blowing of air from the lubrication system. In case of emergency, the manual controls are used. For example, the manual control contains buttons for opening and closing of the die, manual cooling of the die, emergency stop, and various other controls.

3.3 Problem definition

The company mainly manufactures throttle bodies along with other different parts of an automobile. The throttle body (Figure 40) is an air intake system of the automobile which controls the amount of air flowing to the engine, in response to the driver accelerator pedal into the main engine. This part is manufactured in the company by the cold chamber injection process.

Figure 40 Throttle body

The scrap rate of the particular part was analyzed for the month of February 2018. Figure 41 depicts details of the scrap in the form of a histogram chart.

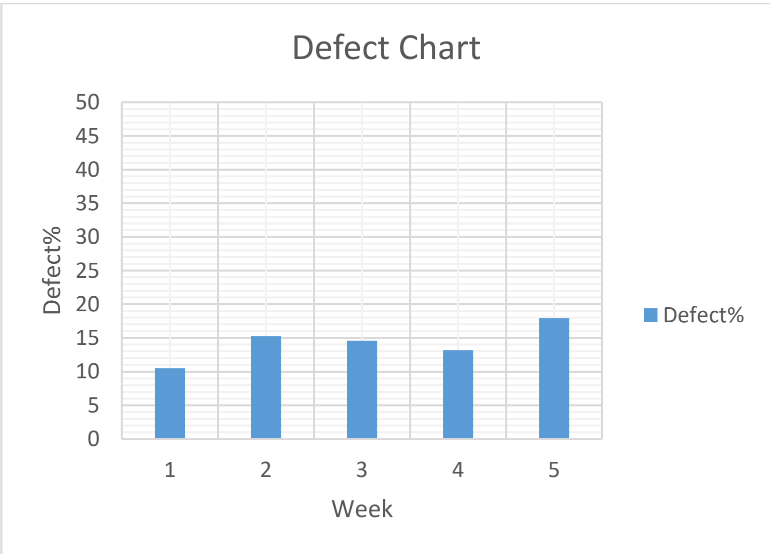


Figure 41 Histogram chart for Feb 2018

In the month of February, on an average, 22197 good parts and 3352 scraps were present. The production cost of one part is 2.086 €. Thus, the company had a profit of 46302.942 € by producing the good parts. The histogram analysis depicts that, the scrap rate was constantly in the range of 10-20% over the entire month, which accounted for a loss of approximately over 7000 € for the month of February. According to the industry, this was considered a major loss. Figure 42 depicts a chart differentiating the number of defective parts to good parts respective to the production days of the week.

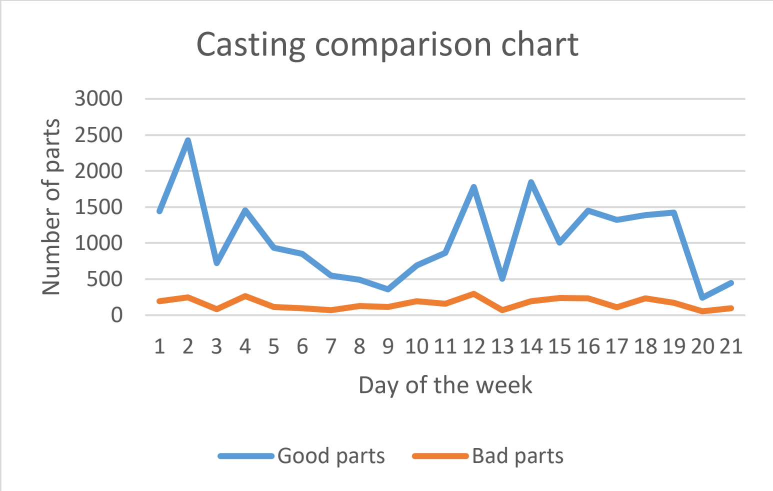


Figure 42 Comparison of productive and defective parts for Feb-2018

The project mainly focusses on understanding the process parameters that are related to the defects and determining the best set of parameters that can be utilized to reduce the scrap rate.

To study the reason behind the scrap rate, a pie chart was created to analyze the type of the defect found. Figure 43 shows the type of defects that are frequently occurring during the period.

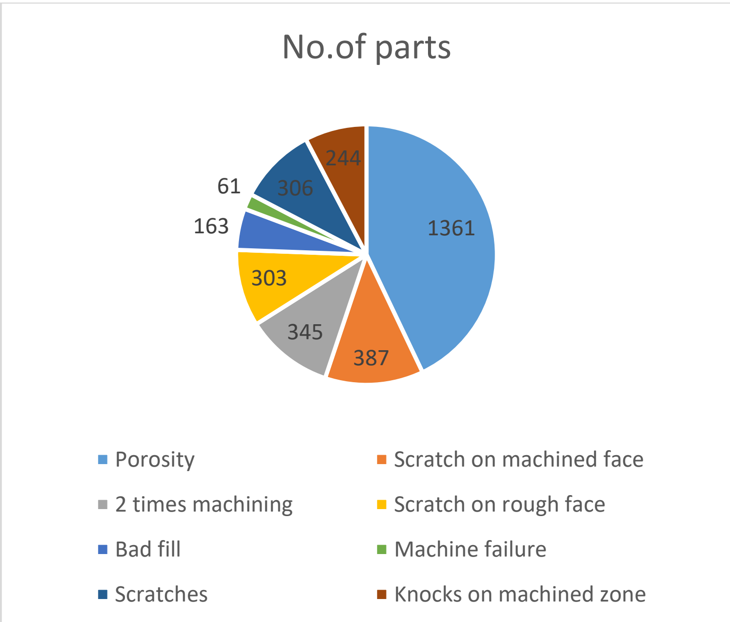


Figure 43 Pie chart for the type of defect Feb 2018

It is evident from the pie chart that porosities, scratches on machined face, two times machining, scratch on the rough face, bad fill, machine failure, scratches and knocks on the machined zone are the commonly occurring defects. Among these, porosities, scratches and bad fill were considered to be the most frequently happening defects.

Porosity is a defect that occurs on the surface or within the casting in the form of small holes. Porosity can be of two forms, namely shrinkage porosity or gas porosity. Gas porosities are the result of gases trapped during the cavity filling, whereas shrinkage porosities are the result of the delay in solidification in various regions.

Bad fill is a defect that occurs when the molten metal is unable to fill the cavity. When the molten metal flows into the cavity at insufficient velocity and also if the die is too hot than required.

Scratches on the machined face and roughed face are formed due to various reasons. In this case, it could be due to shrinkage, thermal imbalance and uneven ejection force exerted by the plunger during injection.

The defect, 2 times machining happens after machining in CNC. Sometimes, due to inappropriate machining, the casting is passed the second time for machining. But this results in over-machining, thus, rejecting the casting.

The porosities are further divided according to the affecting position, namely diameter 21 and diameter 42, which are crucial positions for the product.

Figure 44 depicts a part containing scratches on the rough face. Figure 45 and Figure 46 show a part containing porosities in diameter 21 and diameter 42, respectively. Diameter 21 and diameter 42 relate to the names of the defects according to the design configuration.

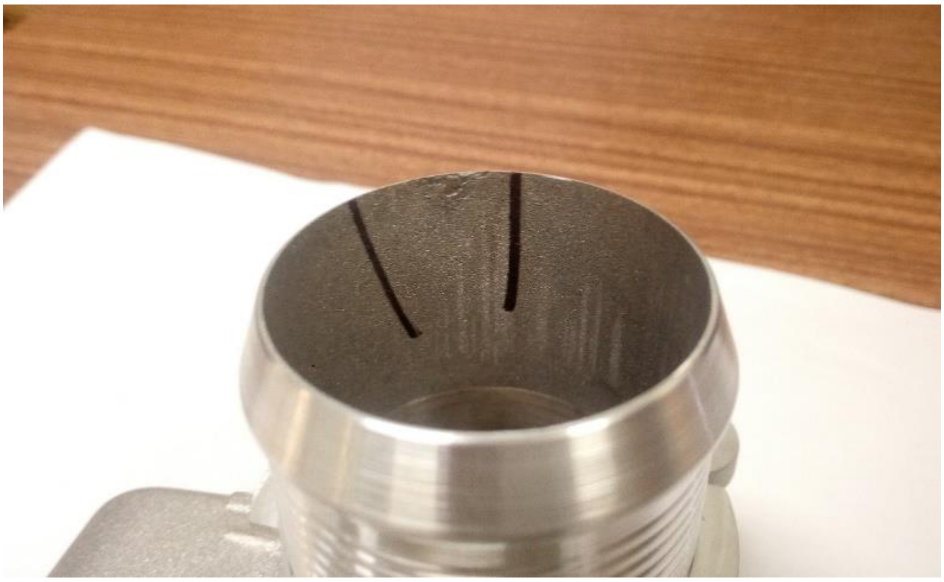


Figure 44 Scratches on the rough surface

Figure 45 Porosity in Diameter 21

Figure 46 Porosity in Diameter 42

3.4 Brainstorming

Brainstorming sessions were conducted with people from process control, floor workers, production supervisor, and quality control. It is understood from the graph that porosity and scratches on the machined face are the main type of defects that were frequently occurring. The bad filling was another defect that was a major cause of concern.

The brainstorming session began with analyzing the type of defect occurring after machining. The process of HPDC was explained by the production supervisor and the parameter details were explained by the process control supervisor.

Discussions were focused on parameters such as injection parameters, die condition, the composition of molten metal and about the machine. The molten metal that the company utilizes is an Aluminum alloy with a composition of AlSi9Cu3. The lubrication process is carried out in 5 steps or zones, with different values of pressure and height in different zones. In order to minimize the effort and time to do quality analysis, a control robot and sensors are attached near the machine to dispose of parts that are not compatible with INESC system. The INESC system is a system consisting of sensors to detect the non-conformities in design and quality of the part.

After the brainstorming session, as part of the quality analysis, an Ishikawa diagram was created to understand the reasons behind the occurrence of the defects. Figure 47 shows the summary of factors that caused a various defect.

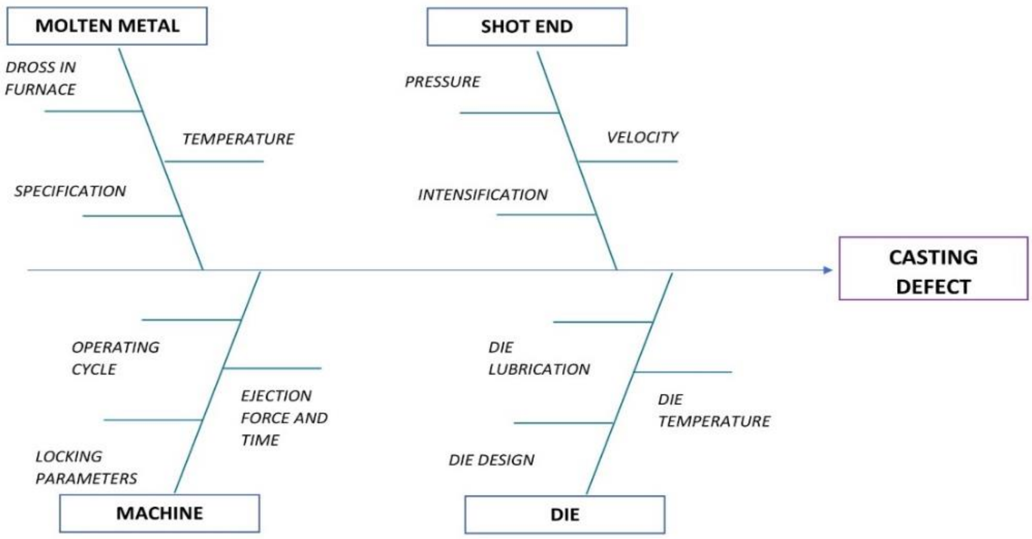


Figure 47 Ishikawa diagram for casting defect

The root cause for the occurrence of these defects was divided into molten metal, shot end, machine and die related defects.

These problems were further analyzed to determine the exact reasons for the occurrence of defects.

The first cause to analyze was molten metal. During the formation of molten metal, dross or slags are formed. Slags are usually related to ferrous alloys whereas, dross formations are related to non-ferrous alloys. Dross is formed when the molten metal contacts the air surrounding the furnace. It is a mixture of aluminum and oxide films. Some of the primary reasons for dross formation include:

- Turbulence;
- Oxygen surrounding the scrap;
- Dirt, oil or contaminants on the scrap;
- Improperly adjusted burners;
- Over-heating of the scrap;
- Incomplete pressure control.

The effects of dross formation are porosity and entrainment defect.

The temperature of molten metal also has an important effect on the occurrence of defects. Improper temperature affects the fluidity of the metal. Higher the temperature increases fluidity but can also establish a reaction between the material and the mold.

Viscosity, surface tension, inclusions and solidification pattern of aluminum alloy are characteristics that affect the fluidity and quality of the casting. Higher the viscosity, surface tension, and inclusions decrease the fluidity and hence, degrading the quality of casting.

With regards to shot end related defects, velocity, pressure, and intensification of molten metal are parameters that have a larger contribution. All of these parameters have effects on porosity and mechanical properties. The velocity in die casting is divided into the first stage and second stage velocity. Larger the velocity and intensification pressure, increase the porosity distribution.

Thus, to produce a good quality casting, high intensification pressure and lower flow velocity are required.

Die also plays an important part information of surface defects on the casting. Die design, die lubrication and die temperature are the primary reasons for the occurrence of defects. As per experimental studies, the optimum die temperature must be approximately 200^{o}C. Temperature below 200^{o}C leads to the occurrence of air porosities and cold flow. Casting of an alloy into a mold with insufficient surface temperature results in fall of alloy temperature. Thus, resulting in cold joints and cracks on the surface of the casting.

The lubrication of die plays an important part in maintaining the thermal imbalance of the die. It is important to regain the original temperature of the die after every shot. Thus, the amount of spray, the type of lubricant and angle of spray must be carefully considered.

After a series of discussions, porosity and bad filling were considered to be the main defects that lead to reducing the scrap rate. There were specific regions of the part where the porosity was frequently occurring, and they were characterized according to the diameter of the particular region.

The parameter detail currently utilized by SONAFI is shown in Table 3.

Table 3 Parameter details

PARAMETER	MIN	SET	MAX	UNITS
Plunger velocity 1st stage	0.04	0.07	0.100	m/s
Plunger velocity 2nd stage	4.50	5.5	6	m/s
Specific Pressure	950	1000	1250	Bar
Time between Point 1 to Point 2	1450	1800	2100	Ms
Starting distance for 2nd stage	250	270	285	Mm
Die temperature	-	175	-	^{o}C

The definition of each parameter is described below:

- Plunger velocity 1st stage is the velocity of the plunger at the initial stage of injection, pushing the molten metal inside the shot sleeve;
- Plunger velocity 2nd stage is the velocity of the plunger at the final stage of injection, pushing the molten metal into the cavity;
- Specific pressure is the pressure of injection;
- The time between point 1 and point 2 is the duration of the plunger from the 1st stage to 2nd stage;
- Die temperature is the temperature of the die before the injection process.

3.5 SWOT analysis

SWOT stands for strengths, weaknesses, opportunities, and threats. It is an important tool for interpreting the characteristics of a method or topic. SWOT is a decision-making tool that initiates this thesis work.

Strength and opportunities help to achieve organizational goals or objectives [67]. Weaknesses and threats are contrary to them. Likewise, strengths and weaknesses are influenced by the internal environment, whereas opportunities and threats are influenced by the external environment.

Here, SWOT analysis was justified for the quality tools, Taguchi method for Design of Experiments (DOE), numerical simulation and for the strategy used.

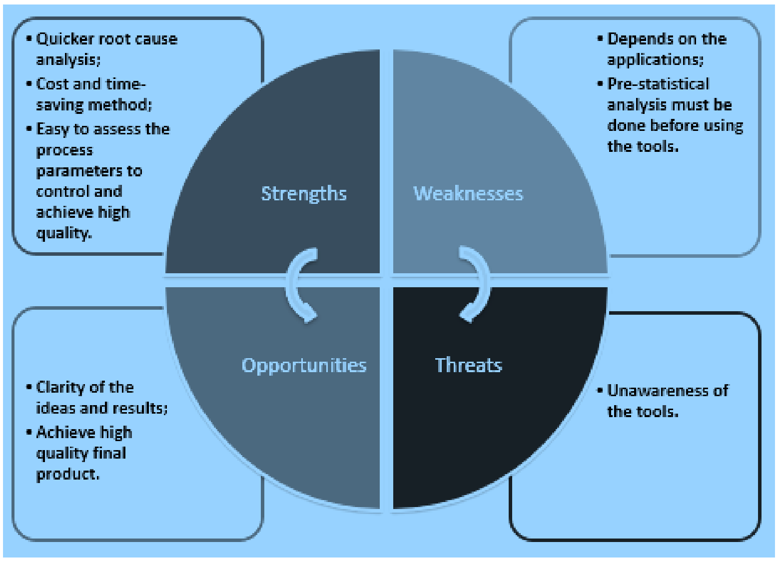


Figure 48 SWOT analysis for implementing quality tools

Primarily, SWOT was carried for utilizing quality tools (Figure 48). As mentioned before in the literature review, quality tools are simple tools to analyze a method easily. The strengths include quicker root-cause analysis and cost and time savings. The root cause analysis enabled to assess the process parameters associated in order to produce the high-quality casting.

The main weakness commonly encountered in the use of quality tools is that it is application demanding. It is important to have detailed information about the process before using the tools.

The main threat to these methods is the unawareness of the tool. This tool can be easily constructed and understood, but it requires pre-requisite knowledge. For example, a person working on the shop floor does not need to know the process. Thus, these analyses are not required for him/her. But, if this information is understood by the shop floor, it can be advantageous for improving the process.

Opportunities include preparation of strategies for future work provided by the clarity of ideas and results from the analysis.

The second SWOT analysis was carried for utilizing Taguchi and ANOVA method (Figure 49). The strengths include the ability to easily develop new products and improve existing products also. Usually, during a process, there are factors such as an environment that does not directly affect it but plays a crucial role. These factors are considered as noise factors and DOE methods allow to include them during optimization.

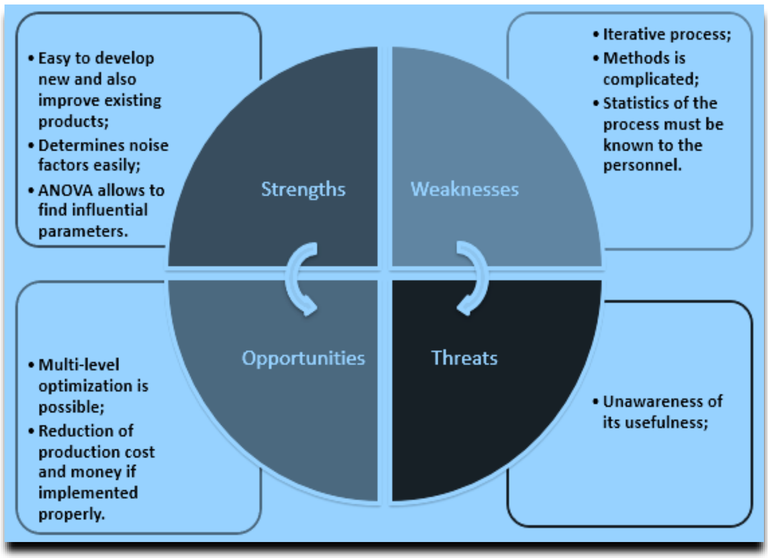


Figure 49 SWOT analysis for Taguchi method and ANOVA

The weakness of DOE and ANOVA analysis is that it is a complicated and iterative process. Before performing DOE, statistical and quality analysis must be done to scrutinize the main factors to experiment in DOE. Thus, the effect of the abovementioned analysis depends on results obtained through these analyses.

The weakness of this method is also the unawareness of the tool. There are many optimization techniques after performing DOE. Multi-level response optimization and fuzzy logic can be done to improve the process

Thus, the Taguchi method of DOE was chosen as it was relevant to the optimization needed. After Taguchi, ANOVA was used to determine the significance of the parameters.

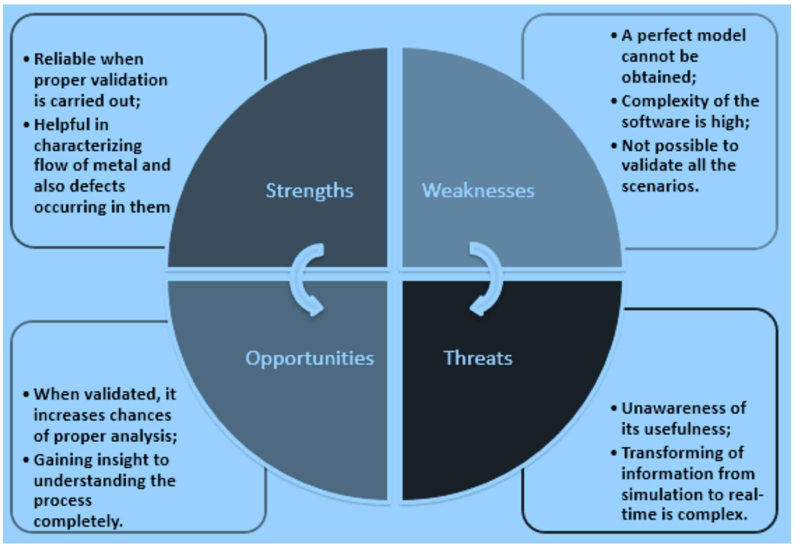


Figure 50 SWOT analysis for numerical simulation

The third SWOT analysis was done to use the numerical simulation for a process like die-casting (Figure 50). Numerical simulations proved to be very influential during the decision-making stage, as mentioned in the literature review. With the simulations, it was possible to characterize the molten metal flow and defects occurring in the parts.

The main weakness of this method is that not all the scenarios in the process can be validated. For example, it is not possible to experiment with certain factors such as pressure, or time between stage 1 and stage 2 velocity. Thus, a perfect model cannot be obtained.

The main threat to this method is that, its unawareness too. But, in spite of this unawareness, most of the foundry industries utilize numerical simulation during the preliminary stage of designing.

Another threat commonly faced after carrying out numerical simulations is the transformation of simulation results to real-time machining. Even though most of the time, the results are almost similar in both, since simulation does not allow to validate all the scenarios surrounding the process, there is a certain risk that the analyzer must take to implement.

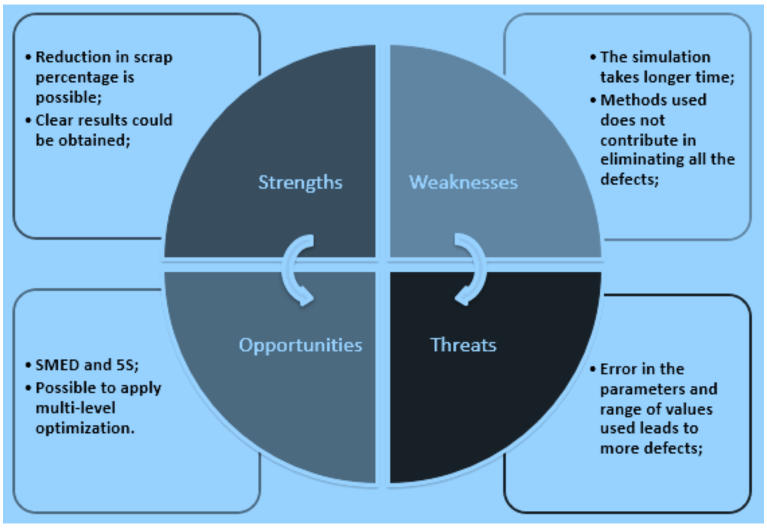


Figure 51 SWOT analysis for an adopted improvement strategy

The final SWOT analysis was carried out for the strategy adopted to improve the process and reduce defective products (Figure 51). The main objective of the thesis is to analyze process parameters and optimize. This could be achieved with the help of beforementioned tools and techniques. Thus, the SWOT analysis was justified for the methods used for optimization.

The strengths of this strategy include a reduction in scrap percentage and a proper understanding of the process.

While analyzing the defects, it was found that some of the rejections were present, which does not occur due to parameters, but due to other processes involved after casting such as machining. Thus, this improvement technique might not be useful in eliminating all types of defects.

Careful considerations must be taken before finalizing the experimental process parameters for DOE. This is because a wrong set of parameters will yield different results.

The opportunities provided after using this strategy is the ability to apply lean techniques such as SMED and 5S.

3.6 Preparation of the experiments

3.6.1 Definition of the variables to control and their interdependence

The control factors have a significant effect on the percentage rejection. The parameters can be set and maintained by the manufacturer but cannot be changed directly by the customer. Noise factors include variations in the environmental operating conditions. The parameters must be carefully considered in order to reduce the rejections. The Ishikawa diagram was used to identify the main parameters to control. The parameters along with their levels are shown in Table 4.

Table 4 Parameter levels for DOE

PARAMETER	LEVEL 1	LEVEL 2	LEVEL 3	UNITS
Plunger velocity 1st stage	0.055	0.06	0.065	m/s
Plunger velocity 2nd stage	4.75	-	5	m/s
Specific Pressure	975	1000	1025	Bar
Die temperature	195	200	205	^oC
Pouring temperature	670	675	680	^oC

The main difference between the parameters used by the industry and the parameters proposed for the experiments is the die temperature. The die temperature is one of the most important parameters in the casting process, as the difference in the level of temperature affects paint coating of the part, lowers the liquid metal temperature and increases the liquid metal flow. It also enhances the material properties. Lian-Qing Ji [68] performed experiments to review the effect of microstructure and density at 100^oC, 150^oC, and 200^oC. In the particular experiment, it was found that, at 150^oC, the material properties could be increased, thus reducing some of the majorly occurring casting defects.

3.6.2 Defining the matrix of experiments

After finalizing on the set of parameters designed for the experiment, it is needed to develop a matrix to be analyzed in Minitab software. Here, we have three different parameters with one parameter at two levels and other parameters at three levels. Thus, the Degree of Freedom for the design is L18 (Figure 52):

Figure 52 DOE for the parameter set

Thus, the L18 orthogonal with 18 experimental runs have to be selected from the list of available Taguchi Designs (Table 5).

Table 5 L18 Orthogonal array from Minitab

S.no	Plunger velocity 2nd stage (m/s)	Die temperature (Celsius)	Pouring temperature (Celsius)	Plunger velocity 1st stage (m/s)	Pressure (Bar)
1	4.75	195	670	0.055	975
2	4.75	195	675	0.060	1000
3	4.75	195	680	0.065	1025
4	4.75	200	670	0.055	1000
5	4.75	200	675	0.060	1025
6	4.75	200	680	0.065	975
7	4.75	205	670	0.060	975
8	4.75	205	675	0.065	1000
9	4.75	205	680	0.055	1025
10	5.00	195	670	0.065	1025
11	5.00	195	675	0.055	975
12	5.00	195	680	0.060	1000
13	5.00	200	670	0.060	1025
14	5.00	200	675	0.065	975
15	5.00	200	680	0.055	1000
16	5.00	205	670	0.065	1000
17	5.00	205	675	0.055	1025
18	5.00	205	680	0.060	975

3.6.3 Practical approach: Defining the methodology used in the experiments

An overview of the methodology used for the improvement process is presented:

- The methodology used in the experiment begins by understanding the process of die casting;
- The problem faced by the company was determined with the use of certain quality tools such as the Ishikawa diagram and histogram analysis;
- The beforementioned analysis done leads to the study of the current process parameters utilized by the industry and then, a study was done on the probable parameters that can be applied to the process;
- The set of parameters finally obtained was designed in a way to analyze with the help of Minitab;
- Experiments were conducted on the shop floor and parallelly numerical simulations were also performed;
- The results of the analysis in Minitab and numerical simulations were used to perform a three-hour production run on the shop floor.

The methodology used in the design of the experiment can be described as:

- The first task is to assign response variables, which are the dependent variables that undergo changes during a casting process. Evidently, defect percentage is used as the response variable;
- Next, control variables are assigned. The control variables are independent variables that have a different effect on the casting. The control variables used are plunger velocity 1st stage and 2nd stage, die temperature, aluminum pouring temperature and pressure;
- After brainstorming and analyzing using various quality tools, the parameter table was designed. They were designed at different levels according to machine capability and guidance of the supervisor;
- A total of 18 sets of combinations were used and 5 sets or 10 parts per experiment were considered, which totals 180 die casting samples;
- The experiments were conducted on the cold chamber die casting machine and then arranged for machining;
- The defects confronted by the part are identified after machining. But, defects such as porosity in the internal regions of the part cannot be seen through the naked eye. They are determined by imaging through an X-ray microscope;
- In order to understand the temperature distribution of the die, thermographic images were taken using the thermographic camera. Images were taken of the movable die and fixed die.

Signal-to-noise ratio	Goal of the experiment	Data characteristics	Signal-to-noise ratio formulas
Larger is better	Maximize the response	Positive	$S/N = -10 *\log(\Sigma(1/Y^2)/n)$
Nominal is best	Target the response and you want to base the signal-to-noise ratio on standard deviations only	Positive, zero, or negative	$S/N = -10 *\log(\sigma^2)$
Nominal is best (default)	Target the response and you want to base the signal-to-noise ratio on means and standard deviations	Non-negative with an "absolute zero" in which the standard deviation is zero when the mean is zero	$S/N = 10 \times \log((\bar{Y}^2) \div \sigma^2)$ The adjusted formula is: $S/N = 10 \times \log((\bar{Y}^2 - s^2 \div n) \div s^2)$
Smaller is better	Minimize the response	Non-negative with a target value of zero	$S/N = -10 *\log(\Sigma(Y^2)/n))$

Figure 53 Signal to noise ratio description [67]

Figure 53 shows different types of signal to noise ratio in Minitab software.

Signal to noise ratio indicates the relation between the response variable and the input variable. It measures the behavior of the response variable under different noise conditions.

The signal to noise ratio is divided into four categories:

- Larger is better;
- Nominal is best;
- Nominal is best (Default);
- Smaller is better.

Each of the categories has its own characteristics and is chosen according to the goal to achieve.

1. Larger is better characteristic is used in order to maximize the response variable. For example, to maximize the quantity of production or to maximize the yield of the process. This entity mostly yields positive target value;
2. Nominal is the best characteristic is used in order to achieve an optimum response. For example, to determine the economic order quantity. The target value can be positive, negative or zero. Also, the target value is based on the standard deviation;
3. The third category is "Nominal is best (Default)" characteristic. When no other options are selected, this category is used as default. The properties of this category are similar to the one above but differ in the formula and the result depends on both the mean and standard deviation. The target value is non-

negative with absolute zero, in which the standard deviation is zero when the mean is zero;

4. The final category is "Smaller is better". This category is used to minimize the response variable. The final result is non-negative.

The goal of the thesis is to reduce the defects, thus, "Smaller is better" characteristics is used.

3.7 Numerical simulation

Simulations were performed to see the effect of various parameter levels. The simulations were carried out in Quikcast software. Before beginning the simulation, a fine mesh of the concerned part was first made in Visual Viewer software. This meshed part was used to carry out the simulation. The main focus was to check the temperature distribution, the fill time and the total shrinkage porosity. Quikcast is a casting simulation and process evaluation software. It discourses about the basics of any casting process, such as filling, solidification and porosity production. It helps in providing a complete industrial solution and also provides realistic prediction at each step of the casting process. As problems faced by any casting industry, the software enables to cut costs and reduce time. It can be used in the early stages, such as mold and process development and also for part quality assessment.

The methodology for numerical simulation depends on the factors leading to the aforementioned defects. Although, the simulation allows the use of a limited number of parameters that include, die temperature, metal temperature and 1st stage and 2nd stage velocities. The conditions given for the numerical simulation are shown in Table 6.

Table 6 Experimental parameters data set for the numerical simulations

Number	1st stage velocity [m/s]	Die Temperature [°C]	2nd stage velocity [m/s]
1	0.55	200	5
2	0.6	195	4.75
3	0.65	205	5

3.8 Results and discussions

3.8.1 Summary of the results obtained

In the Taguchi method, there are two terms to represent the output characteristics. The term 'signal' refers to the desired value for output characteristics and the term 'noise' refers to the undesired value for output characteristics. The SN ratio replicates the average and variation of the quality characteristics. Thus, the die casting components are manufactured against the trial conditions given in Table 5. Experiments are conducted for five shots or ten castings. Subsequently, the percentage of rejection for each experiment is calculated. Since the optimal goal is to minimize the rejection rate, the lower the better characteristics, is selected and SN ratios are calculated. The rejection percentage is determined by using the formula:

Equation 2 Formula to determine the rejection percentage

Rejection percentage = (Number of castings defective/Total number of casting produced)*100

The next step is to determine the characteristics of Minitab, that signifies the goal to fulfill. In Minitab, there are four types of response characteristics. Here, in this analysis, the "Smaller is better" characteristic is used. Further information is given in section 3.6.3 (Practical approach: Defining the methodology used in the experiments). Table 7 shows the rejection percentage for all the experiments after production in the shop floor.

Table 7 Rejection percentage for the experiments

Serial number	Plunger velocity 2nd stage (m/s)	Die temp. (^oC)	Pouring temp. (^oC)	Plunger velocity 1st stage (m/s)	Pressure (Bar)	Defect (%)
1	4.75	195	670	0.055	975	0.56
2	5	195	670	0.06	1000	0
3	4.75	200	675	0.055	1000	0
4	5	200	675	0.06	1025	0
5	4.75	205	680	0.055	1025	0
6	5	205	680	0.06	975	1.1
7	5	200	680	0.055	1000	1.1
8	4.75	200	680	0.065	975	0.56
9	5	205	670	0.055	1025	0
10	4.75	205	670	0.065	1000	0.56
11	5	195	675	0.055	1000	0
12	4.75	195	675	0.065	1025	0
13	4.75	205	675	0.06	975	0
14	5	205	675	0.065	1000	0
15	4.75	195	680	0.06	1000	1.1
16	5	195	680	0.065	1025	0.56
17	4.75	200	670	0.06	1025	0
18	5	200	670	0.065	975	0.56

Taguchi analysis for the different set of parameters was performed. This analysis enables to determine the best set of parameters to minimize the defects.

Figure 54 depicts the main effects plot for SN ratios. The main objective of the project is to reduce defects and thus, the SN ratio should be minimum. The parameter level that has the lowest SN ratio is selected for trial in the shop floor.

The main effects plot for SN ratios was plotted using Minitab software. Before performing ANOVA, the effects of each of the parameters can be determined using main effects plot. The main effects plot compares the means of different parameters in order to determine the optimum level. Here, the five parameters, namely plunger velocity 1st, and 2nd stage die temperature, pouring temperature and intensification pressure were used to plot.

The first parameter, the plunger velocity 2nd stage has different means with respect to the level of the entity; die temperature, pouring temperature, plunger velocity 1st stage and intensification pressure have mean values at three levels. The lower mean values correspond to smaller signal t noise ratio. From this analysis, it is evident that the value of each parameter in order to obtain a good quality casting is,

- 4.75 m/s for plunger velocity 2nd stage;
- 200 ^{o}C for die temperature;
- 680 ^{o}C for pouring temperature;
- 0.55 or 0.65 m/s for plunger velocity 1st stage;
- 975 bar for intensification pressure.

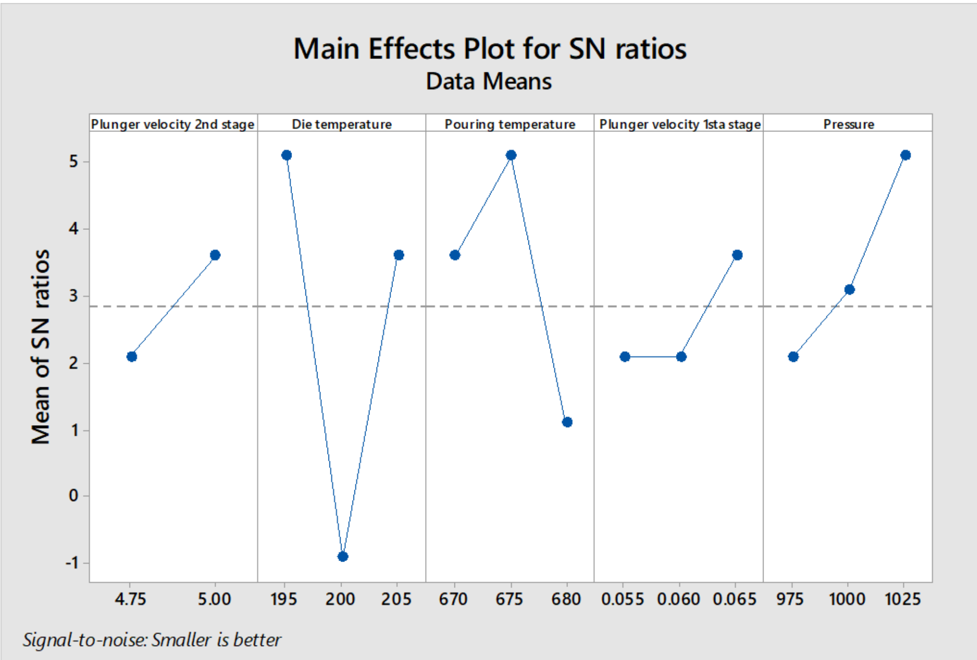


Figure 54 Main effects plot for SN ratios

The Minitab also allows determining the effect of interactions between two parameters. Figure 55 shows the interaction plot for the parameters.

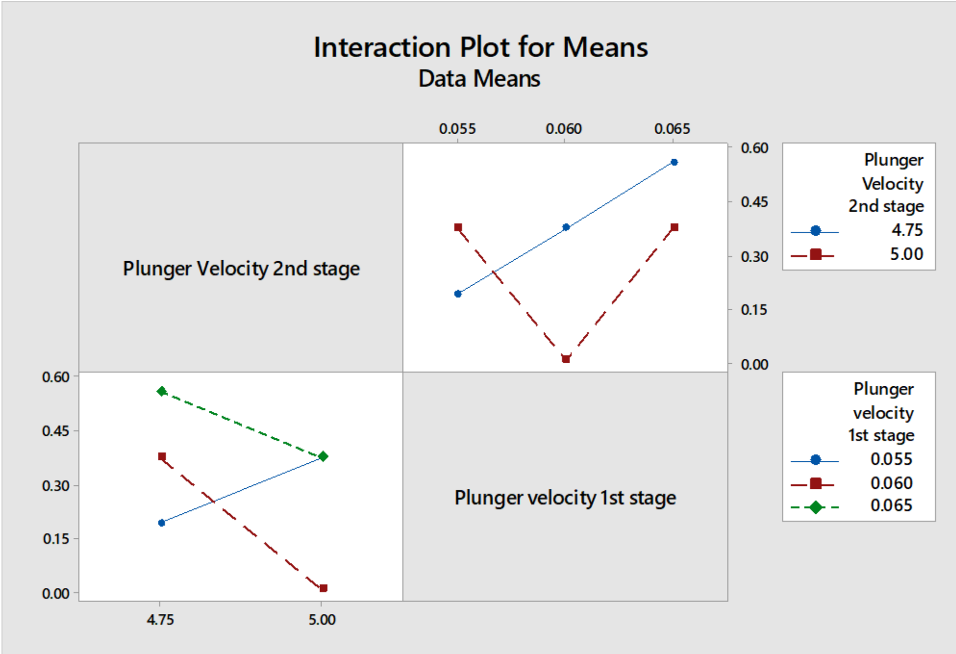


Figure 55 Interaction plot for means

Interaction plots are used to determine the effect of variables which are not independent. If the lines are parallel, it means that there are no interactions between the variable, whereas when the lines are non-parallel, it means that there are interactions between the variables. More the lines are non-parallel, stronger is the relationship between the variables.

Here, it is seen that the relationship between the percentage of rejection and plunger velocity 2nd stage depends on the plunger velocity 1st stage. If the 1st level (0.055 m/s) of the plunger velocity 1st stage is used, then the 1st level (4.75 m/s) of the plunger velocity 2nd stage has greater mean value and likewise for other levels.

The optimum level of rejections in the die casting process was also determined with the aforementioned parameters, which is described in 3.11 (Critical analysis of the final result: Best set of parameters achieved).

3.9 ANOVA analysis

ANOVA is a statistically based, objective decision-making tool for detecting any differences existing in the average performance of a group of items tested. In order to determine the significance of the parameters, an ANOVA analysis was carried out. It is evident from Figure 56 that the pouring temperature significantly affects the occurrence of defects but contributes to just 10% of the defects.

Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Plunger Velocity 2nd stage	1	92.96	92.96	92.96	0.30	0.604
Die temperature	2	147.60	147.60	73.80	0.24	0.795
Pouring temperature	2	1031.84	2139.16	1069.58	3.45	0.100
Plunger velocity 1st stage	2	950.81	950.81	475.40	1.54	0.289
Specific Pressure	2	693.61	693.61	346.80	1.12	0.386
Plunger Velocity 2nd stage* Plunger velocity 1st stage	2	1305.02	1305.02	652.51	2.11	0.203
Residual Error	6	1857.74	1857.74	309.62		
Total	17	6079.58				

Figure 56 Analysis of Variance for SN ratios

Adjusted sum of squares are measures of variation for different variables. The adjusted sum of squares is used to calculate the p-value for a term. Adjusted mean squares measures how much variation a variable possesses. Unlike Adj SS, Adj MS consider the degrees of freedom.

F-value is the test statistic used to determine whether the variable is associated with the response. It is used to calculate the p-value. A larger value of F-value means it has a larger effect on the response. Here, it is seen that pouring temperature has a larger effect on response variable than other variables. Thus, pouring temperature is important in acquiring good quality casting.

3.10 Numerical modeling

The QuikCast software was used to evaluate the results and fit an appropriate model for the experiments. Various process parameters were examined to understand the effect of each on the final result.

The parameters used for performing the numerical simulations were previously given in 3.7 (Numerical simulation). The fill time and total shrinkage porosity were the effects studied using the software.

The results of other simulations are attached in 6.1 (ANNEX1). All the results of the simulations yield almost the same value. Thus, only three results were studied in particular.

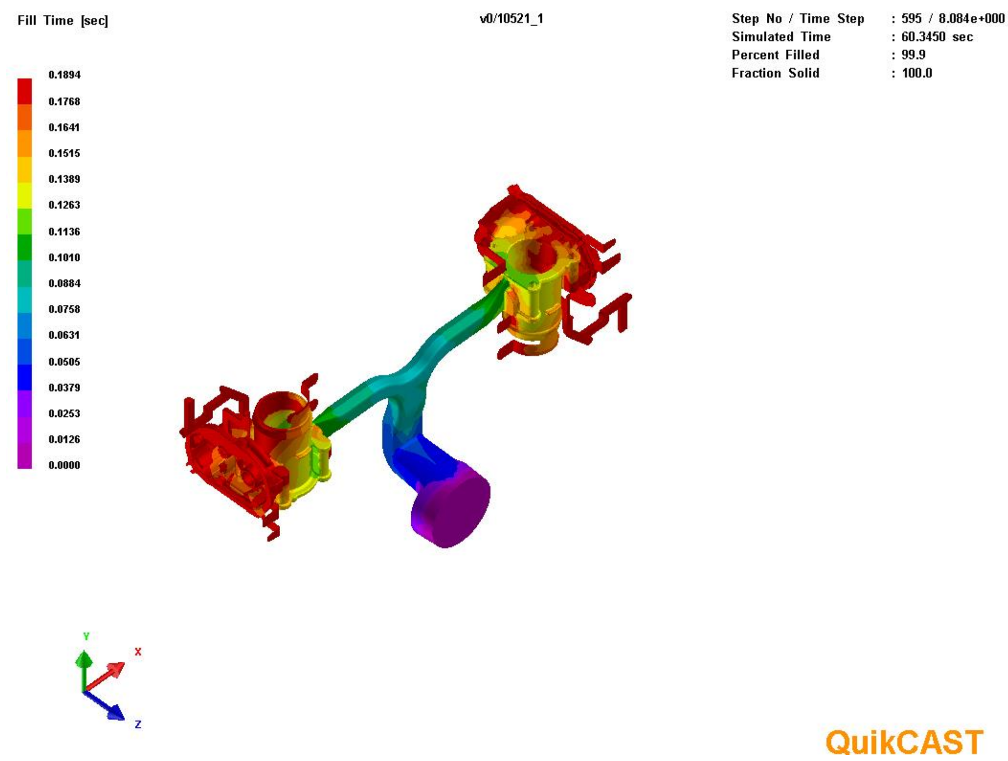


Figure 57 Fill time for the 1st experiment

Figure 57 shows the fill time characteristics of the part. The cavity is filled with molten metal at an average of 0.1500 seconds. Filling time is the duration in which the cavity gets filled by the molten metal.

The red colored regions seen at the corners of the part are critical regions with an average filling time of 0.1894 seconds implying incomplete solidification resulting in the bad filling. Whereas the green colored region signifies the optimum level of filling of molten metal with complete solidification. Blue and violet colored regions signify quicker filling of molten metal. But, in this simulation, it is not significant as it occurs in runner region.

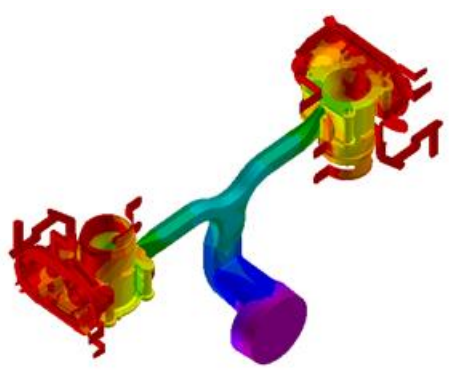


Figure 58 Analysis image of the 1st experiment

Figure 58 shows a magnified image of the simulation result for the 1st experiment. The critical spots are indicated by red colored regions. These regions signify that the molten metal has partially filled in those regions. This means that the molten metal did not solidify after injection. The fill time is influenced by the temperature of the die and injection velocity of the molten metal. The temperature of the die is an important parameter, as mentioned before in the literature review. If the die is too hot, the molten metal overfills the cavity and increases the chances of heat bubbles. But, in this simulation, the molten metal did not reach the corners of the part, where it is evident that the filling time is 0.1890 seconds.

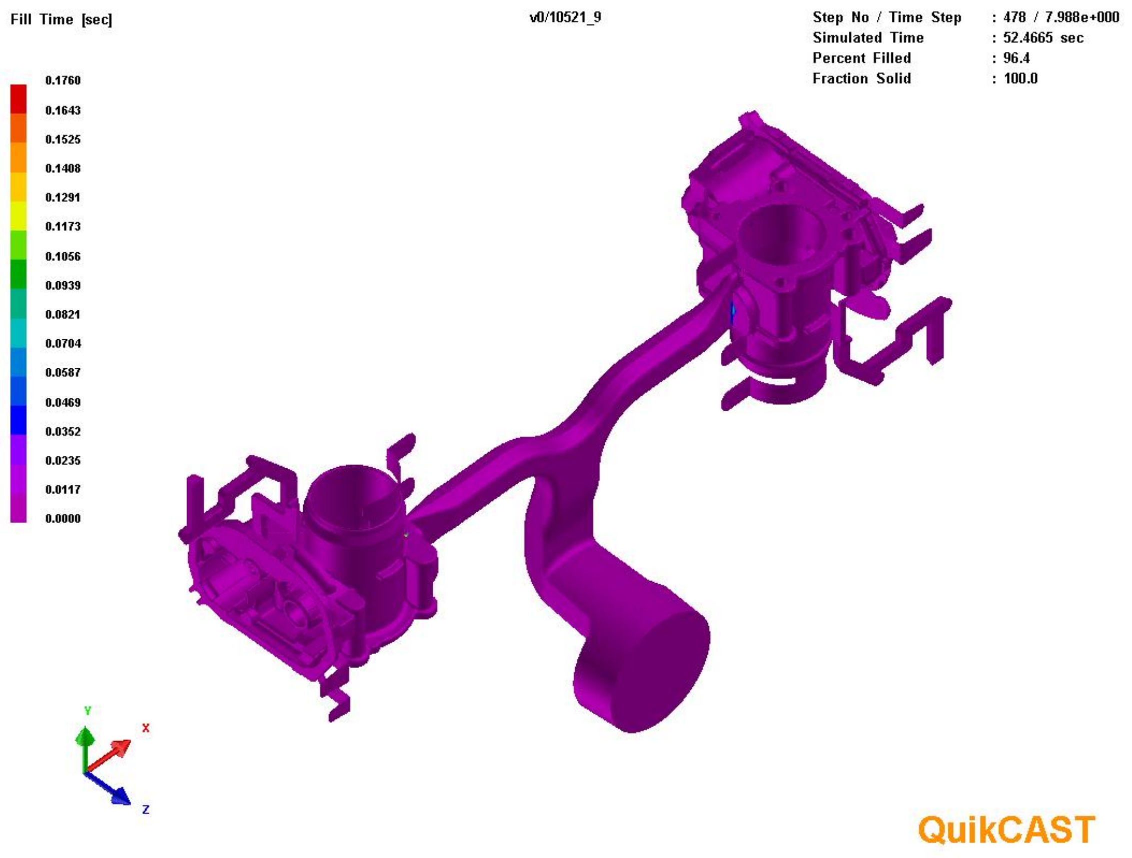


Figure 59 Fill time for the 2nd experiment

Figure 59 shows the filling time characteristics of the 2nd simulation. This simulation yielded different results, compared to the first one. Here, it is seen that the corners of the part did not have any hot-spot region, signifying that the corners of the part were properly filled with molten metal. Another observation from this analysis is that there were no critical regions which were partially filled or solidified. In this simulation, the first stage velocity is 0.060 m/s and die temperature to 195°C compared to the previous simulation.

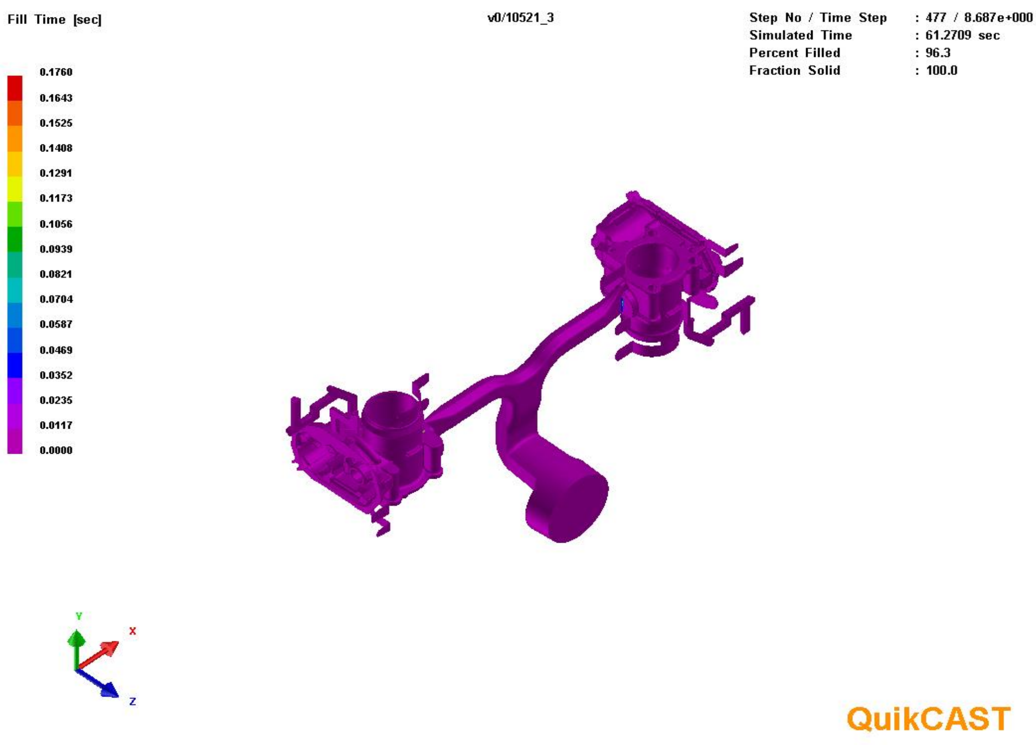


Figure 60 Fill time for the 3rd experiment

Figure 60 shows the of filling time for the 3rd experiment. In this experiment, the temperature of the die and the first stage velocity were further increased to 205°C and 0.065 m/s, respectively. Here, we can notice that there are not critical red colored regions. Instead, more of blue and violet colored region. Since the velocity and the die temperature are high, the molten metal could not completely fill the cavity in most of the critical regions. This is another situation in which the defect known as bad filling occurs.

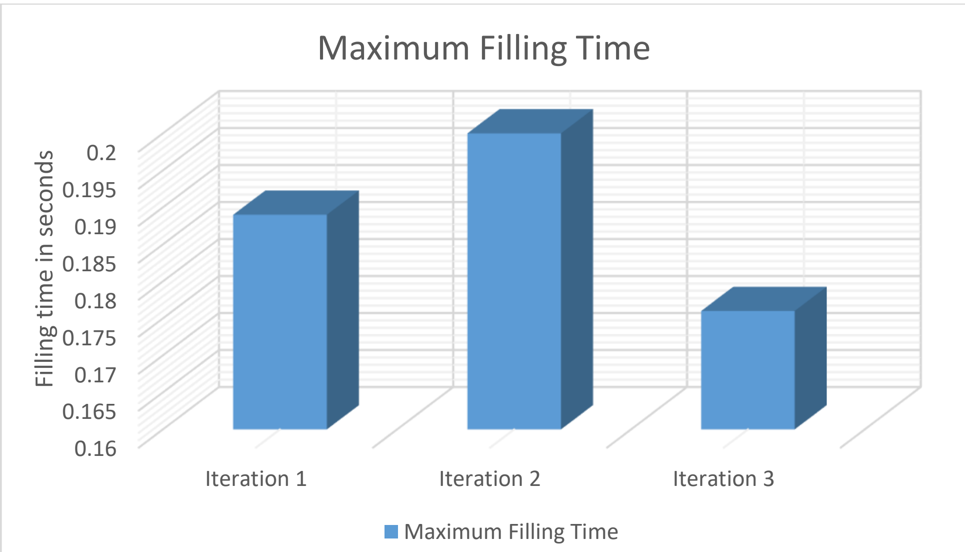


Figure 61 Graphical representation of maximum filling time for each simulation

In order to identify the maximum filling time of a simulation (Figure 61), a 3D clustered column graph was designed. Iterations represent the simulations whereas the blocks represent the filling time.

It is evident that the iteration 2 has the highest filling time, followed by iteration 1 and then iteration 2. Although the second simulation has the highest filling time, it was evident that the part did not have hot spots in the critical region, thus making it the near ideal high-quality part.

The iteration 1 has the second maximum filling time. In this simulation, the cavity got filled for a longer duration, thus resulting in hot spots at the corner of the part. The velocity was too low for an ideal solidification.

The iteration 3 has the lowest maximum filling time. In this situation, the cavity was filled within a short span of time. This is because the 1st stage velocity in this situation was 0.065 m/s, which is 0.05 m/s greater than iteration 2. This characteristic influenced the bad filling defect in certain regions of the part, eventually resulting in rejection.

Thus, more focus was directed towards determining the optimal 1st stage and 2nd stage plunger velocities. More simulations were performed with different levels of the plunger velocity and die temperature to understand the fill time characteristic.

Although simulations were performed at the different level of parameters, the result proved to be almost similar to each other. Refer 6.1 (ANNEX1) for results of rest of the simulations.

Figure 62 Total shrinkage porosity for the 1st experiment

Figure 62 depicts the porosity distribution for the 1st experiment. Porosity is a defect that occurs due to various parameters such as plunger velocity and dies temperature. There are no critical regions or regions with hot-spots were identified, signifying that there are no regions with 100% porosities existence. It is evident from the image that the concentration of porosities is around 20 to 30%, meaning that porosity is present but not in larger concentration or cluster of porosities. It is also seen that the porosities were not present in the regions, discussed in 3.3 (Problem definition).

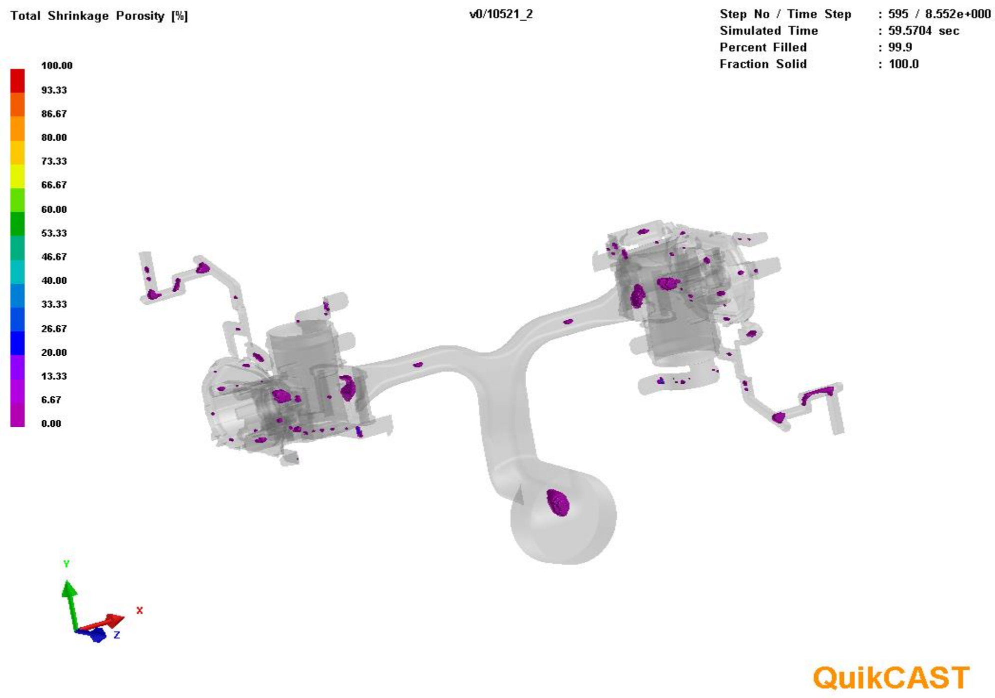


Figure 63 Total shrinkage porosity for the 2nd experiment

Figure 63 depicts the shrinkage porosity for the 2nd simulation. Here, the concentration of porosity is around 20 to 30%, which is similar to the previous analysis. Porosities were mostly present in the bottom of the part, but these areas are not much significant since they are machined, which eliminates the porosities.

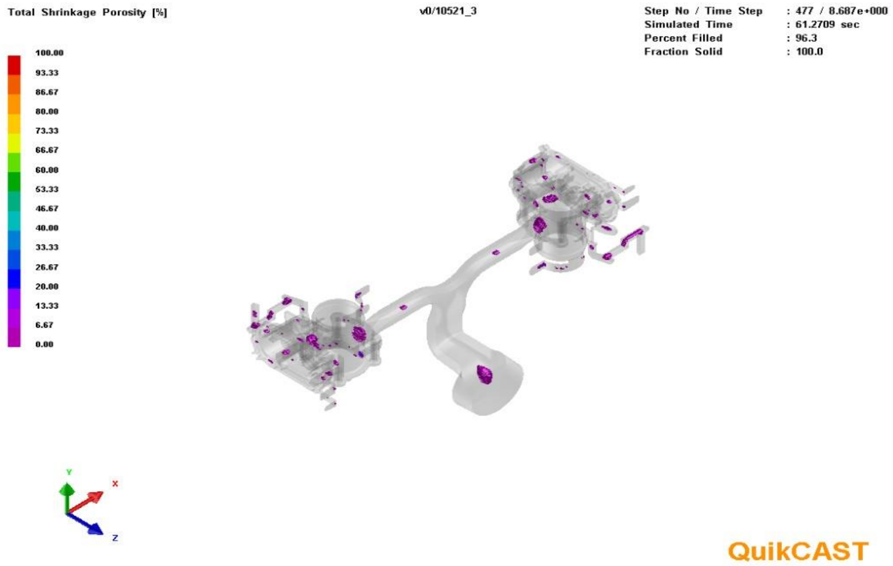


Figure 64 Total shrinkage porosity for the 3rd experiment

Figure 64 depicts shrinkage porosity distribution for 3rd simulation. In this experiment, the concentration of porosity is significant, but the intensity of the porosity remains the same at 20 to 30%. There are certain regions in the part that have larger clusters of porosities. Parts are also rejected by the company when the concentration of porosity is high at any particular position.

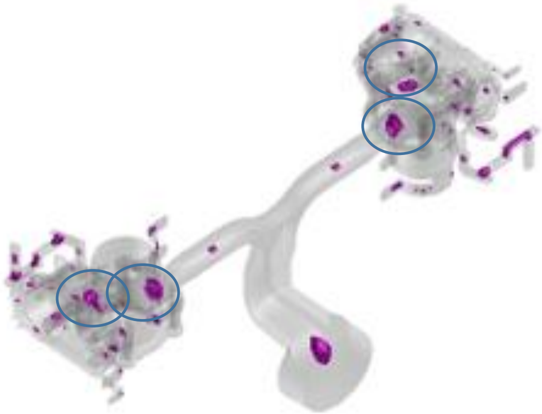


Figure 65 Representation of cluster of porosity marked by a circle

The areas highlighted by a circle in Figure 65 are the positions where big clusters of porosity are present. This happens because, the second stage velocity was too high, and the die temperature was more than desired, leading to the eruption of bubbles in the parts and eventually leading to porosity and bad filling.

From the figures representing the fill time, it is evident that the mold is filled at an average duration of 0.1100 to 0.1875 seconds. This signifies that the mold is filled at an optimum duration according to the specification mentioned in Table 3, making the casting to solidify completely before removing it out. The advantage of having an optimum fill time enhances the ability to obtain castings without having a bad filling.

Next, the total shrinkage porosity distributed along the casting is determined using the Minitab software. It is evident from the figures that porosity occurs almost in the same regions in all the experiments. Porosities are more at diameter 21 and diameter 42. The porosities at other spots in the casting are not very significant as they are removed by CNC machine after manufacturing.

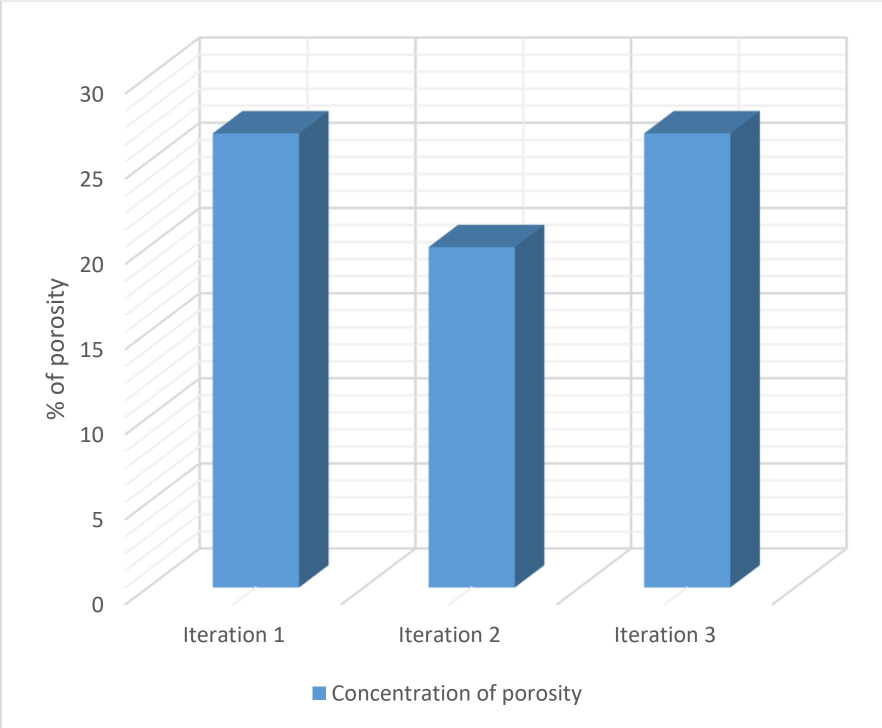


Figure 66 Graphical representation of the concentration of porosity

Figure 66 represents the concentration of porosity on the casting. The concentration of porosity was analyzed for three different simulations. As mentioned before, the average concentration of porosity is 20 to 30%.

3.11 Critical analysis of the final result: Best set of parameters achieved

The analysis in Minitab and numerical simulation in QuikCast software enabled to arrive at the final set of parameters:

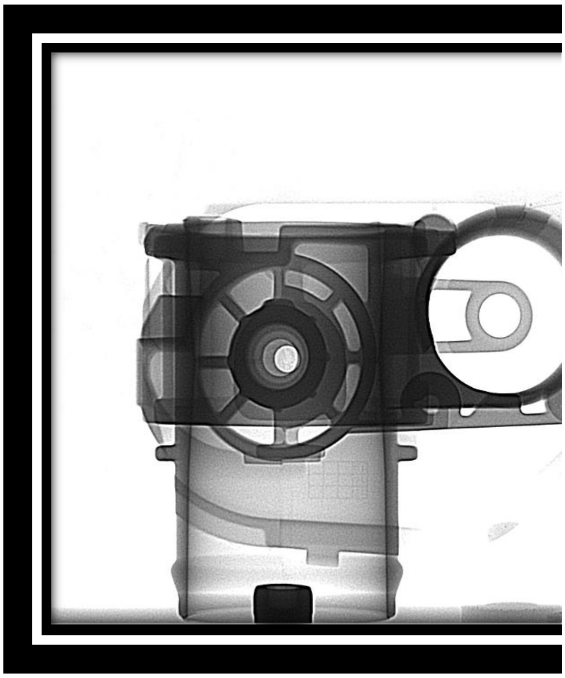
Table 8 Final set of parameters after all the analyses

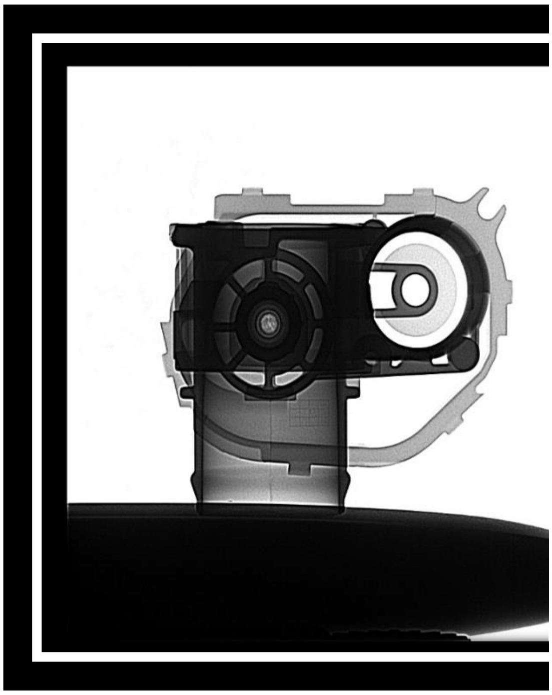
Serial number	Parameter	Values
1	Pouring temperature of Aluminum	680 °C
2	Die temperature	200 °C
3	Plunger velocity 1st stage	0.055 or 0.06 m/s
4	Plunger velocity 2nd stage	5 m/s
5	Specific pressure	975 bar (Multiplicative entity) or 330 bar
6	The time between point 1 and point 2	1750 ms

These parameters were used to perform a 3-hour production run on the shop floor. After machining, the scrap rate was found to be around 7%. No castings were produced with a bad filling defect, but some parts were affected by porosities. Before machining, X-ray imaging was done.

X-ray is a widely used non-destructive testing method to analyze defects not visible to the human eye. It helps in understanding defects such as porosity. Images were taken for 4 out of 10 parts per experiment. This allows checking the difference between the simulation and real-time manufacturing.

A B





C

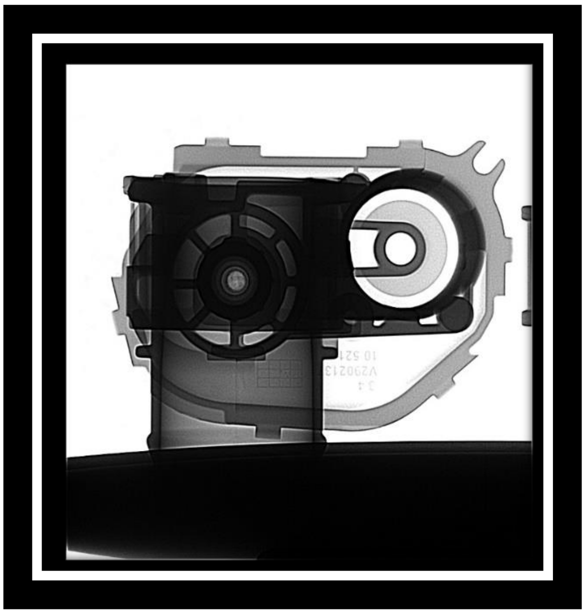


Figure 67 Depicts (A) Good, (B) Bad and (C) Worse castings respectively

Figure 67 shows the X-ray view of the castings at good, bad and worse conditions. These figures show that the simulation results and statistical results correspond to that produced in the shop floor. In the second (B) and third (C) figures, porosities were present in diameter 21 and diameter 42. It is evident that there is the difference between the numerical simulations and real-time manufacturing. But the company's rule is to accept samples with a diameter of porosity lesser than 0.4 mm. The areas which were more open to porosities were not present when the castings were manufactured and machined.

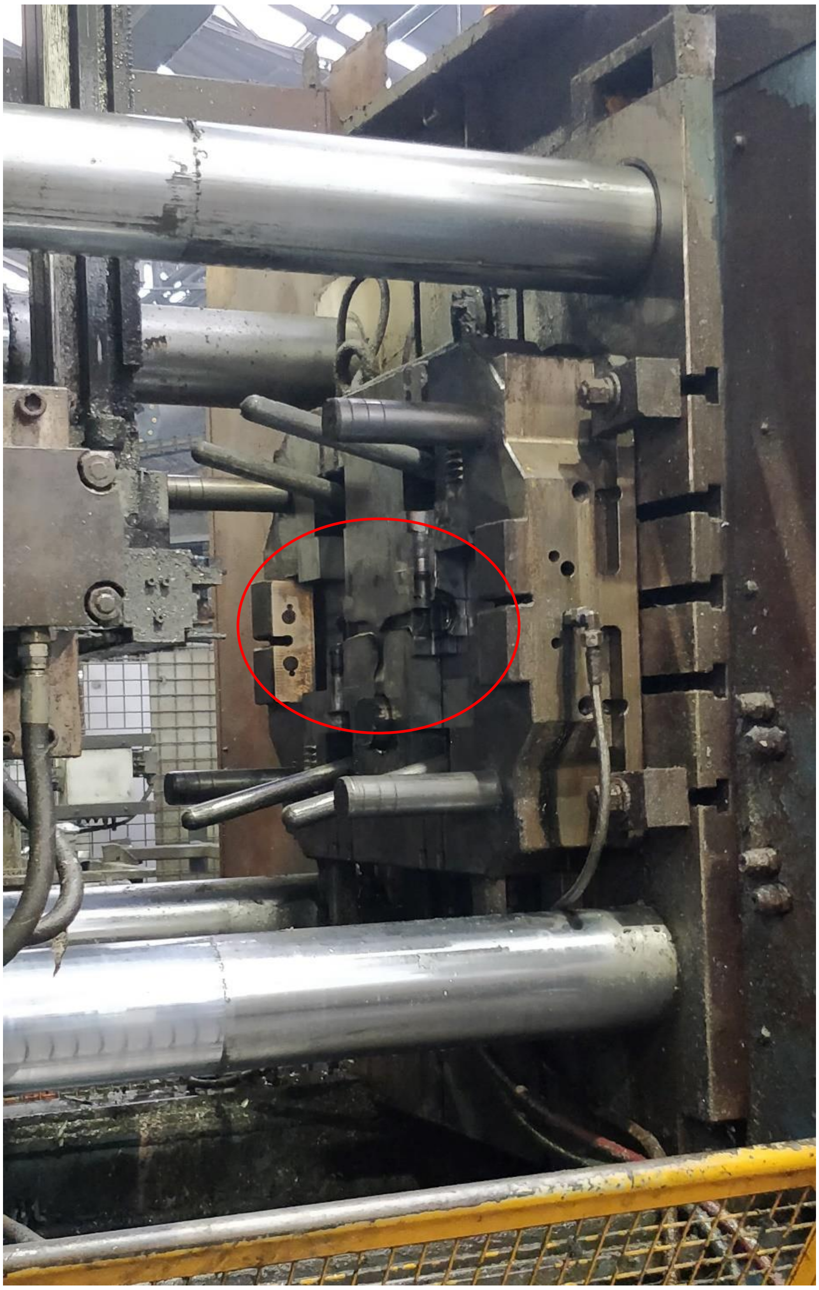


Figure 68 Image of the fixed die of the die casting machine

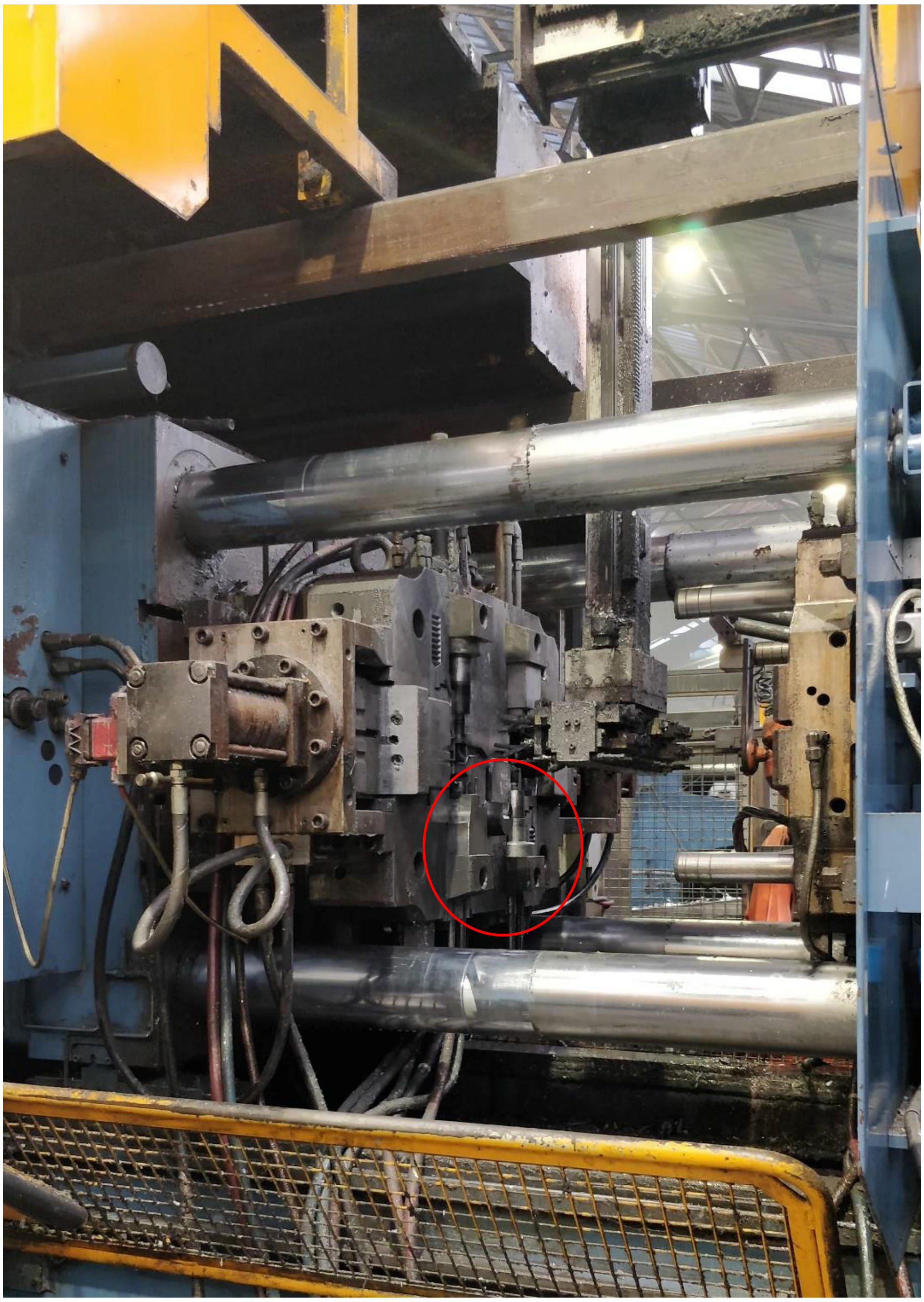
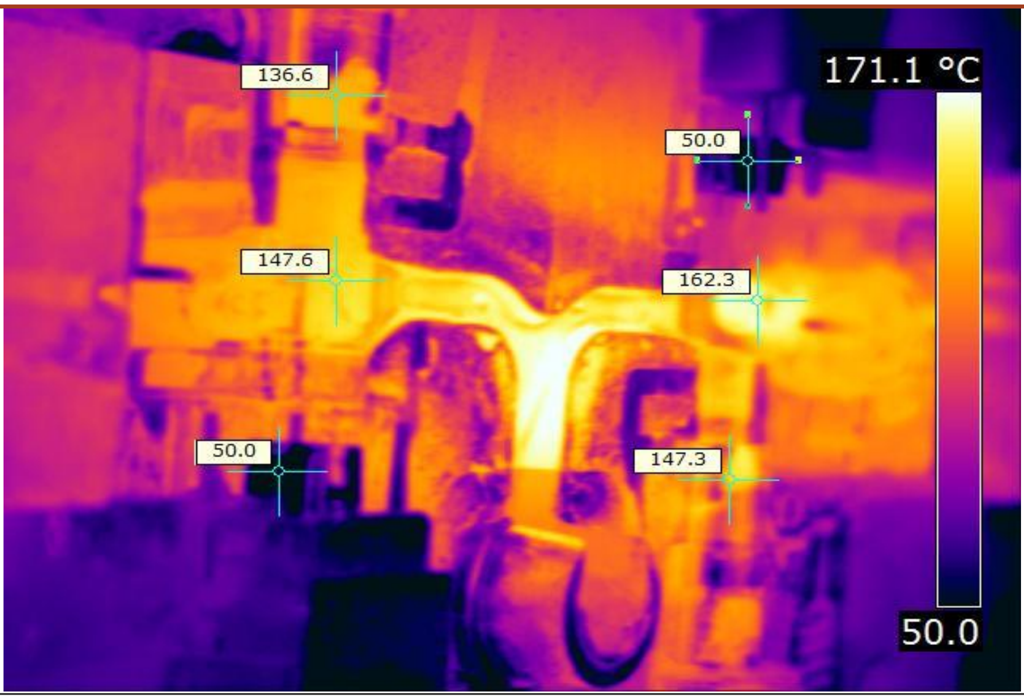


Figure 69 Image of the movable die of the die casting machine

In order to understand the temperature distribution throughout the die, thermographic images were taken.

A



B

Figure 70 Thermography images on the fixed die: A and B represents images of different trials

A

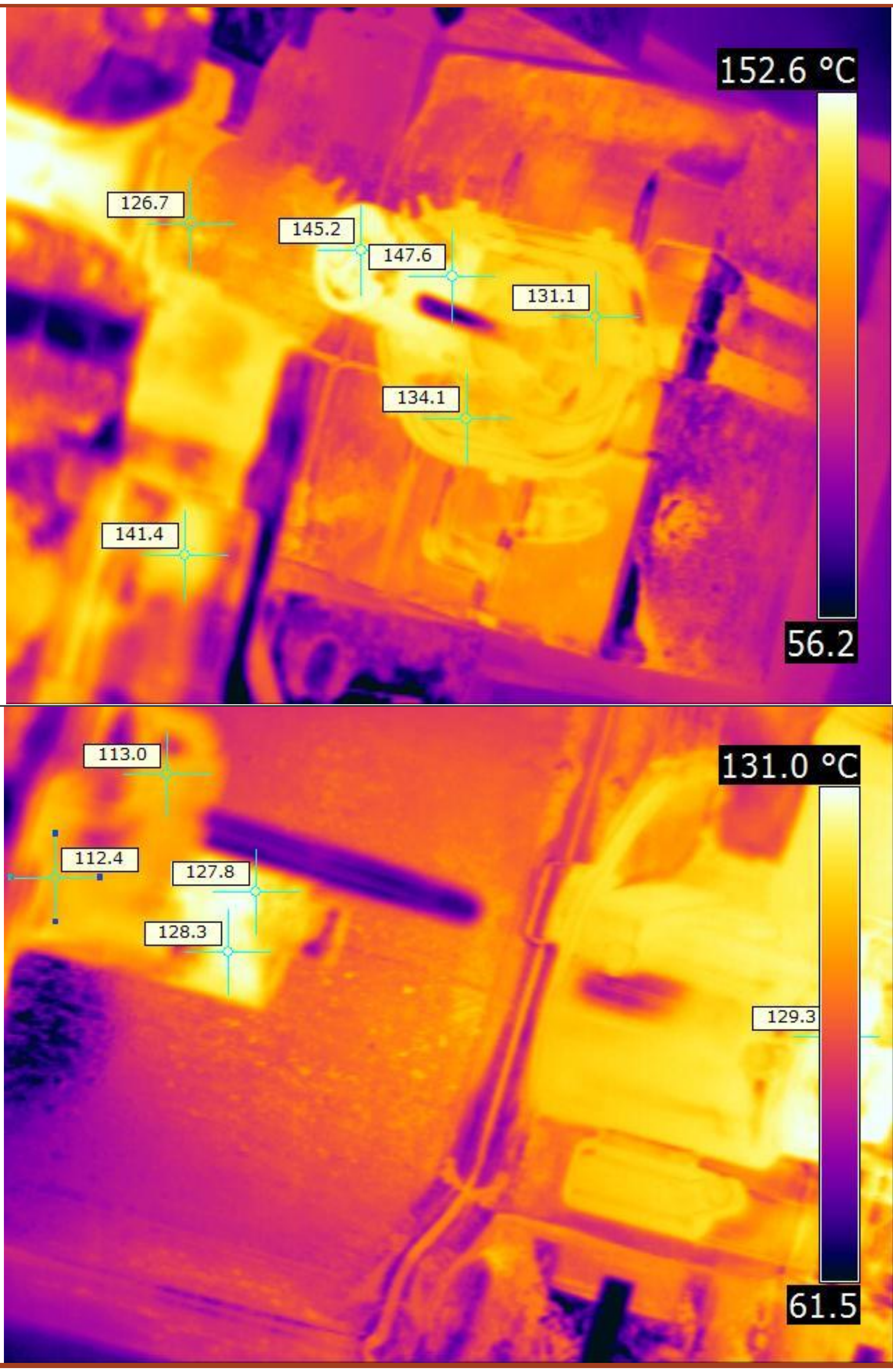


Figure 71 Thermographic images on the movable die: (a) and (b) represents images of different trials

Thermographic images allow monitoring the temperature distribution inside a die. This helps in understanding the behavior of the die at different working conditions. The images were taken after conducting the experiments.

Figure 69 and Figure 68 represents the image of the movable die and fixed die of the die casting machine.

Figure 70 shows a thermographic image of the fixed die in an open state. It is seen that there exists a difference in the temperature from one cavity to another. The temperature in the die ranges from 50^{o}C to 170^{o}C. The desired temperature kept for the die was 200^{o}C but, after each shot, the temperature drops by around 20^{o}C on both the cavities on the fixed die.

In Figure 71, the average difference in temperature is from 152^{o}C to 56^{o}C on the mobile die. It is understood that there is too much temperature difference between both halves of the dies. The temperature distribution in the die is an important parameter because the hotness or coolness of the die results in defects such as bad filling and porosity. Thus, it was important to focus on die and lubrication system used to cool the die.

Observations and problems confronted by the company in terms of occurrence of defects were as follows:

- The first step of analysis begins with characterizing the molten metal using testing procedures such as LiMCA, PoDFA, Prefil testing and reduced pressure test (RPT). These tests help to find impurities, inclusions and hydrogen content inside the molten metal, which are the reasons for the occurrence of defects. Prefil technique is a common method for measurement of oxide films and other inclusions. It is a time-saving testing method. PoDFA is a porous disk filtration technique which allows identifying the types of inclusions but is a time-consuming process. LiMCA is liquid metal cleanliness analyzer which is an in-line technique, but time-consuming and requires expensive equipment. These tests are vital in a die casting industry, but it was not possible to carry out these tests because of time constraints and unavailability of the equipment during the period;
- Secondly, the use of water and air to cool the die after each shot. After each shot, it is important to cool the die, to remove the completed part from the die safely and also without damaging the part or the die. It is a necessity to use the proper amount of lubrication. Defects can occur in the die due to improper amount of lubrication. If the amount of lubricant is not enough, the part may stick to the cavity, leading to defects. Whereas, if the amount is too high, the lubricants take a longer duration to evaporate leading to porosity and poor surface finish. This is the reason why it was challenging to reduce the porosity in the casting. Thus, it is important to choose a lubricant that minimizes overspray, so that it does not clog up the vents. The main problem faced by the company was the inability to

apply the optimal amount of spray, which happened due to the inappropriate pressure of water from the ground level.

CONCLUSIONS

4.1 CONCLUSIONS

4.2 DISCUSSIONS

4.3 PROPOSALS OF FUTURE WORKS

4 CONCLUSIONS AND PROPOSALS OF FUTURE WORKS

4.1 CONCLUSIONS

To sum up, die casting methodology is one of the prominent technologies in the metal forming process. In order to meet demands for higher precision, higher quality and productivity in the present scenario, the optimization of the above casting process is of a great concern for all the manufactures.

The research work was done by understanding the works of previous authors, but also keeping in mind to adjust to the current trend and improve the process. This research work emphasizes on, the use of quality tools, the Taguchi method for DOE and also simulation for optimization. Finally, all of the abovementioned techniques were used in such a way to select the optimal casting process parametric combination to reduce the percentage of reduction.

Table 9 Summary of conclusion

Goal	Achievement	Check
To understand the die casting process used by the industry.	Explained in section 3.2 (Definition of the processes involved in HPDC process).	Done
Identify defects and solution.	Determined the main parameters responsible for the occurrence of defects.	Done
Perform DOE and ANOVA.	DOE and ANOVA was used to find the best set of parameters.	Done
Perform numerical simulation.	The numerical simulation enabled to analyze the characteristic of casting.	Done
Reduce the defect percentage and then follow-up.	Reduced the defect percentage from 14% to 9%.	Done

Table 9 represents a summary of conclusion derived from the thesis.

The main conclusions that can be derived from this thesis are:

- The average reduction in scrap rate after optimizing was approximately 9% from 14%;
- The use of brainstorming technique in an industry to obtain a high precision and practically applicable ideas for optimization;
- The use of quality tools such as Ishikawa diagram to analyze and scrutinize the causes of the defects. Generally, in order to solve a problem regarding the finish of a product or any casting, quality tools such as Ishikawa diagram and histogram chart enabled to determine that the parameters such as plunger velocity 1st and 2nd stage, pressure, die temperature and pouring temperature of aluminum were the main responsible for the defects. The brainstorming technique and the quality tools enabled to determine the range of value of the parameters mentioned in the previous point;
- The use of Design of Experiments and specifically, the Taguchi method for optimizing the process parameters and also reducing the time of computation and time. DOE was performed with the use of Minitab software with the parameters. As the values were robust, Taguchi method was used to analyze and find the final set of parameters;
- ANOVA proved to be an important statistical technique to determine the parameters that were very influential to improve further. After DOE, it is important to determine the most influential parameter that can trigger the defects. The results from ANOVA proved that pouring temperature was the most influential parameter;
- X-ray as a Non-destructive testing method to determine non-conformities with the casting that is invisible to the naked eye of a human. X-ray technique was used to locate the porosities present in the castings. This allows to experiment and also determine the value of the parameter to be used for reducing the defects;
- Thermographic study to understand the behavior of the die after each shot is implemented. Die is an important variant in the high pressure die-casting process. Thus, thermographic images can be taken and used to study the distribution of temperature on the die after each shot, and allowing to analyze the lubrication and cooling system for the die.

4.1.1 Study of the die-casting process and behavior of the parameters

The initial study on the die-casting process implemented by the industry was carried out before beginning the optimization process. This study is described in section 3.4 (Brainstorming). All the variables that are influential to the deviation in the process, that is, the parameters that caused the occurrence of the defects were found out in this section. It proved that the parameters that were causing the problems are listed as follows:

- Die temperature;
- Plunger velocity 1st stage and 2nd stage;
- Pouring temperature of the aluminum;
- Pressure;
- The time between point 1 and point 2.

4.1.2 Benefits of Design of Experiments and ANOVA

Although the parameters were determined, it was important to study the relation between the parameters in order to understand its effects on the die-casting machine or final casting in particular. Design of experiments and ANOVA were the ideologies used to perform the study. This is important because, the parameter- “time between point 1 and point 2”, which is a feature of the time taken by the plunger to reach stage 2 from stage 1, is related to the 1st stage and 2nd stage plunger velocity. The DOE was carried out according to the matrix described in section 3.6.2 (Defining the matrix of experiments). The Taguchi analysis is used because this is a robust process and comprises of varied parameters. Also, it was important to determine the parameter more influential and this was discussed in section 3.9 (ANOVA analysis).

4.2 Discussions

The thesis also allows me to discuss about certain techniques and methodologies that must be used by all the die-casting industries in order to achieve better results. These techniques or methodologies are briefly explained below.

4.2.1 Study/experiments on analysis software

DOE and ANOVA were not merely enough to conclude the results. Thus, the analysis was done on Quikcast software to deeply understand the behavior of the parameters. In the simulations, the percentage of porosity and filling time were studied, the results of which are discussed in section 3.10 (Numerical modeling). These studies enabled to determine the final set of parameters in order to reduce the defects.

4.2.2 Use of quality tools and some continuous improvement techniques

The entire thesis also emphasis on the use of quality tools and continuous improvement techniques. In this thesis, tools such as Cause and Effect diagram and histogram were used to scrutinize the root causes and main defects occurring respectively. The inferences from these tools are discussed in section 3.3 (Problem definition) and 3.4 (Brainstorming).

With respect to continuous improvement techniques, it is important to apply them before, within and after the processes. For example, it is needed to study the thermal behavior of the die, using X-ray technology to determine the concentration of porosity and finally frequent monitoring of personnel and surroundings.

4.3 PROPOSALS OF FUTURE WORKS

Although the aforementioned techniques proved to be useful for optimization, there needs to be done further research in order to improve the condition even more. The proposals for future work include:

- Conducting a fluidity test on the Aluminium alloy to characterize the raw material used for the casting process;
- Studying and analyzing the lubrication system and search for alternative methods of lubrication;
- Using concepts such as kaizen and lean methodologies to improve the working conditions of the entire casting unit and its surroundings.

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5 REFERENCES AND OTHER SOURCES OF INFORMATION

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ANNEXES

6.1 ANNEX1

6 ANNEXES

6.1 ANNEX1

Annex 1 is a table of the type of Aluminum HPDC defects:

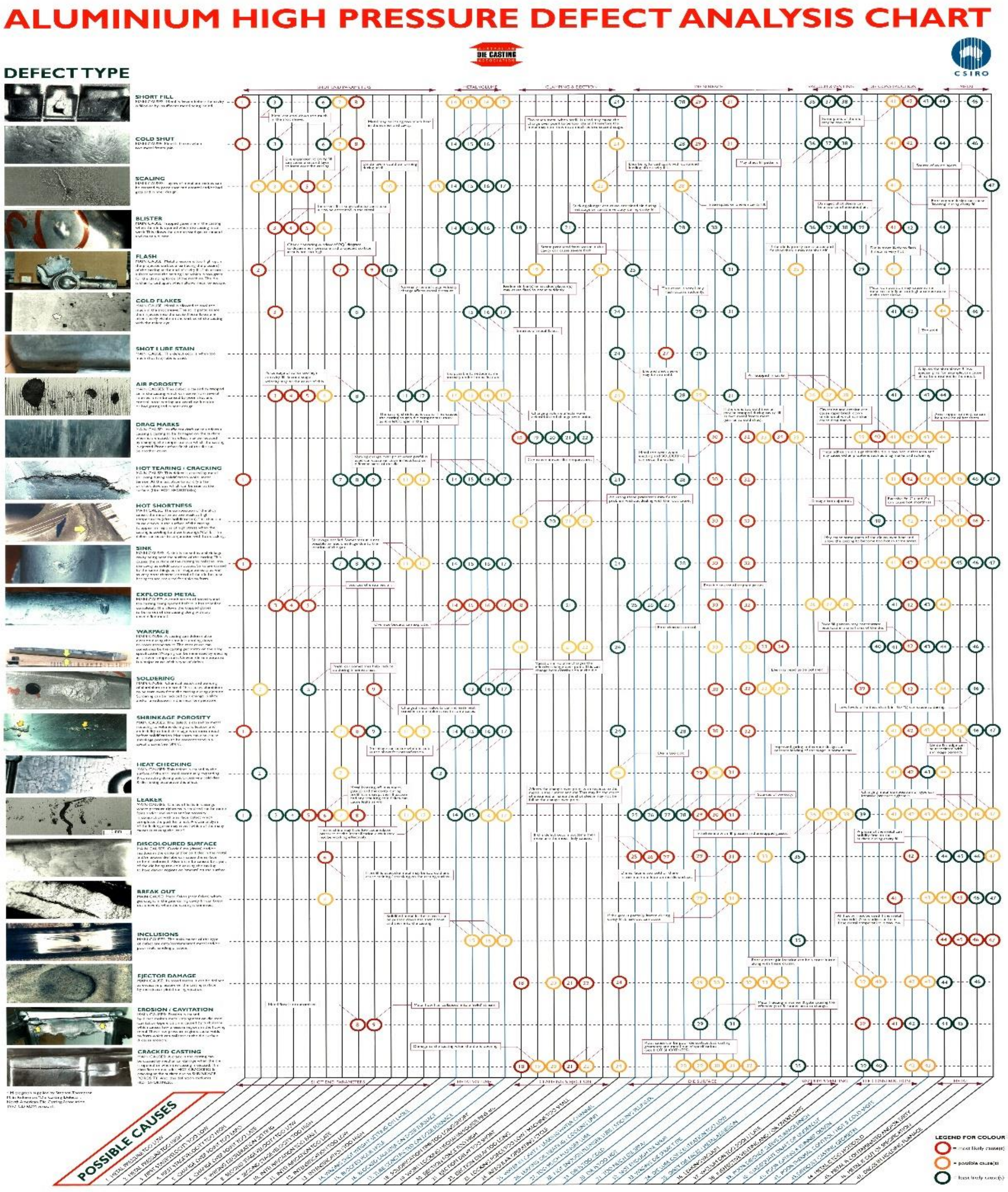

Figure 72 Aluminum HPDC defects by CSIRO