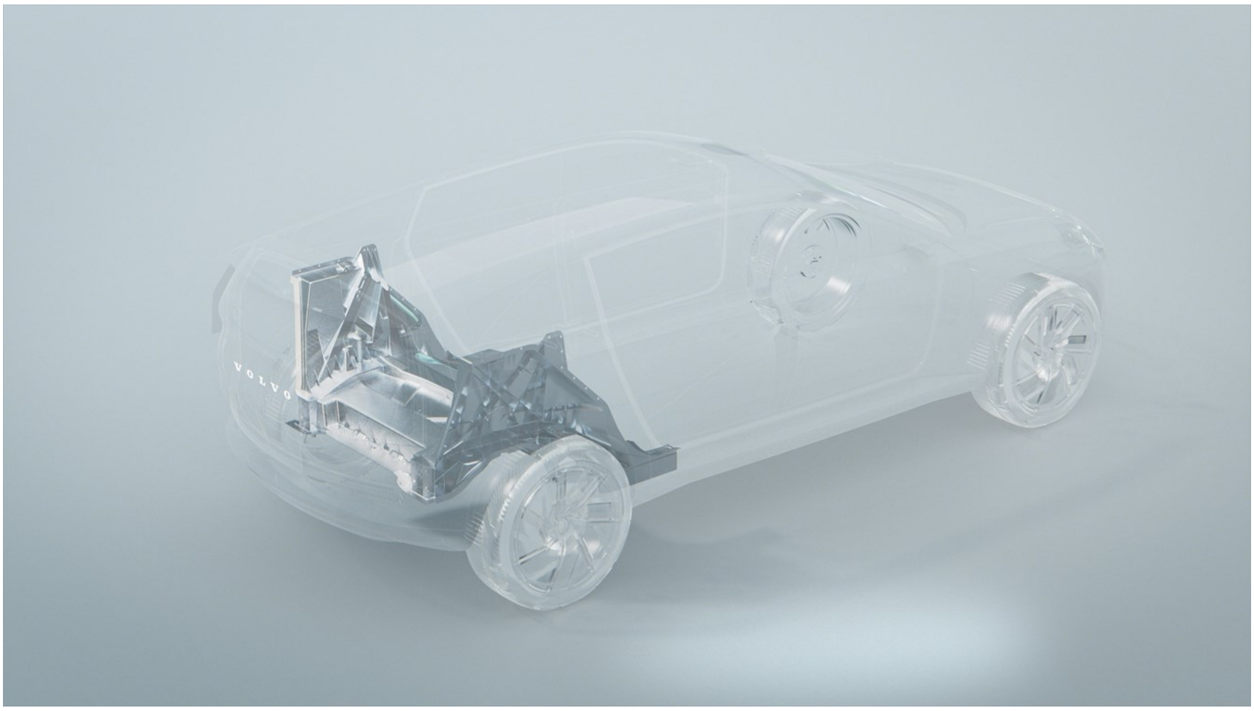

# Improving Quality in Mega-Casted Products

## Identification of contributors to geometrical variation

Master's thesis in Production Engineering

Paul Adam, David Hermez

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
www.chalmers.se

MASTER'S THESIS 2024

# Improving Quality in Mega-Casted Products

Identification of contributors to geometrical variation

Paul Adam
David Hermez

CHALMERS

Department of Industrial and Materials Science
*Production Engineering*
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024

Improving Quality in Mega-Casted Products
Identification of contributors to geometrical variation
Paul Adam
David Hermez



Industrial Supervisor: Josenfin Hansen, Geometry assurance Painted Body VCC
Academic Supervisor: Kristina Wärmefjord, Chalmers University of Technology
Examiner: Kristina Wärmefjord, Chalmers University of Technology

Master's Thesis 2024
Department of Industrial and Material Science
Production Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: The Volvo Mega-Casting [1]

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2024

Improving Quality in Mega-Casted Products
Identification of contributors to geometrical variation
Paul Adam
David Hermez
Department of Industrial and Material Science
Chalmers University of Technology

# Abstract

When using a process to produce various parts, geometrical variation describes the differences in deviations among those parts. These deviations arise due to different factors, and minimizing them contributes to improved consistency in production, increased overall product quality, and reduced costs in terms of extra rework. This master's thesis aimed at expanding the knowledge about high-pressure die-casting (HPDC) and identifying contributors to geometrical variations. The scope of the study is limited to larger defects affecting the geometrical accuracy and excludes surface defects, porosities, and machining. The method used for reaching the goal was by conducting qualitative and quantitative approaches. A total of 11 professionals in the area of HPDC were interviewed. Production tests related to the quenching phase were also conducted in the foundry. The main finding from the study was that design is the root cause of geometrical variations, as the varying thicknesses induce residual stresses which in turn influences the accuracy of the final shape. One of the findings successfully reduced geometrical variation in megacastings but led to other problems such as sticking to the trim-press. In addition, a DoE was suggested for future studies. The DoE provides a systematic way of working and helps in finding the optimal combination of influential and easily changeable parameters.

Keywords: HPDC, Megacasting, Geometrical variation, Distortions.

# Acknowledgements

The authors would like to acknowledge every individual for the support and guidance in completing this thesis. We want to express our gratitude to Volvo Cars for giving us the opportunity to be the first students to expand the knowledge about megacasting. We are extremely grateful to our industrial supervisor Josefin Hansen for the invaluable guidance and advice throughout the project. We also want to thank the examiner Kristina Wärmefjord for the insights and feedback. Big thanks go to all the interviewees for sharing their expertise, insights, and experiences. Their contributions gave us a deeper understanding and enriched this project with practical perspectives.

Paul Adam, David Hermez, Gothenburg, June 2024

# List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

| | |
|---|---|
| AC | Air Cooling |
| ANOVA | Analysis of Variation |
| BIW | Body in White |
| CAD | Computer-Aided Design |
| DOE | Design of Experiment |
| DOF | Degrees of Freedom |
| EFL | Effective Flow Length |
| EV | Electric Vehicle |
| GROMCAP | Geometrical Robustness of Mega Casted Aluminum Parts |
| HPDC | High Pressure Die Casting |
| IHTC | Interfacial Heat Transfer Coefficient |
| MRA | Mold Release Agent |
| PAG | Polyalkylene Glycol |
| PFZ | Precipitate Free Zone |
| RDM | Research Design Methodology |
| SQ | Spray Quenching |
| UTS | Ultimate Tensile Strength |
| WC | Wind Cooling |
| WQ | Water Quenching |
| YS | Yield Stress |

# Contents

# List of Figures

# 1
# Introduction

This chapter introduces the topic of mega-casting, provides a comprehensive view of the concept, and the reason behind manufacturing companies' shift toward mega-casting. It also describes the high-pressure die-casting (HPDC) process chain, the goals of the research, and its limitations.

## 1.1 Background

The world is evolving rapidly, new innovative products are manufactured every day to reduce the environmental footprint, and one of these products is the electric vehicle (EV). However, with new products, new challenges arise and it's well known that electric batteries increase the weight of the vehicle. Therefore weight reduction becomes a new challenge in the new upcoming EVs to enhance energy efficiency [2] and increase range to travel longer distances [3].

The Swedish car manufacturer, Volvo Cars, is investing in a new revolutionary way of HPDC to manufacture parts for their upcoming EVs. The process includes large-scale casting which will minimize the resources needed to assemble large floors, an essential part of Body in White (BIW) products. The concept is called – mega-casting. Mega-casting simplifies the assembly process by reducing welding processes, shortening the assembly line, and decreasing the likelihood of assembly errors. This new concept aims to replace many small parts with a single larger part [4]. It will lead to at least 35% CO2 emission reduction and 50% of the aluminium used will be a secondary alloy. Volvo also expects design optimization of mega-casted parts to enable a 15% weight reduction compared to steel alternatives. Several automakers, including Mercedes-Benz, are investing in large injection molding machines. Moreover, Chinese startups like NIO and Xpeng have also placed orders for these machines [3].

Limited experience with mega-casting poses new challenges. One of the main challenges with large-scale parts is the tendency of geometrical variation. Geometrical variation refers to the deviation of a product's shape and size from its nominal design [5].

A research project, *Geometrical Robustness of Mega Casted Aluminium Parts*, (GROM-CAP), is conducted by Chalmers University of Technology in collaboration with Volvo Cars and other actors to expand the knowledge about mega-castings. This master thesis is part of the GROMCAP project within the work package that covers the identification of sources of geometrical deviation and variation.

## 1.2 Geometrical Variations

The development of modern technology has led to an increase in accuracy in manufactured parts, however, geometrical variations are not eliminated [6]. Geometrical variation refers to the differences in deviations among various parts produced using the same process [2]. In fact, these geometrical variations are process-related. In addition, the deviation is present in all stages of product realization [6]. These deviations can impact the product's shape, size, and characteristics [7]. When these deviations are large enough the product might not function, causing a huge loss for the manufacturer and in the best scenario extra rework. During the use phase of a product, physical phenomena such as thermal expansion, add up the geometrical variation causing a loss of product quality [6]. Twisting, bending, warping, and shrinkage are examples of geometrical deviation. In this thesis, these terms are commonly referred to as distortion and deformation.

## 1.3 Purpose and Goal

The goal of this thesis work is to establish a deeper knowledge of the HPDC process geometry effects and establish a way of working for further studies within the research project.

The purpose is to identify the contributors to geometrical variation to improve the quality of mega-casted products. Distortion and shrinkage are common geometrical challenges in casting and addressing their causes in mega-casting becomes essential.

### 1.3.1 Project Scope

The project scope involves researching key aspects of the HPDC process. Since the concept of mega-casting is new, the research will be based on HPDC products in general. small, medium, and large-sized products. The project scope consists of the following:

- Literature study to understand and map high pressure die casting (HPDC) process.
- Literature study to understand and map contributors to geometrical variation in high pressure die casting.
- Perform workshop and interviews with experts within casting and casting simulation.
- Create cause and effect diagram for contributors to geometrical variation in high pressure die casting for mega casted parts.
- Perform correlation study of measurement data and process data.

- Create a proposal of ranking of variation sources that are of importance on how a mega-casted part will deviate on part level.

## 1.4 Research Questions

Key questions that the thesis work will answer, are the following:

- What are the contributors to geometrical variation in mega-casted products/-parts?
- What are the most crucial contributors?

## 1.5 Limitations

This project has a limited time frame and therefore the scope of the project also requires clear limitations. The areas excluded due to limitations could be investigated in future work. The limitations of the project are:

- **Limited Resources**: The mega-casting is under development and not many studies have been published, which makes the exploration of this area confined.
- **Human Factor**: The mistakes made by the operator will be excluded. Assuming that all parameter settings in the machine are correct.
- **Post-Casting Processes**: Machining, painting and joining will be excluded.

# 2

# Theory

This chapter is a summary of the literature review that gives the reader an understanding of the concepts necessary to fully understand the process of HPDC.

## 2.1 Important Terminologies

In this section, the terminologies needed for understanding the thesis will be explained, covering both the machine level and part level. Figure 2.1 shows the basic terminology of the HPDC machine that will be used in this project.

- **Fixed Die**: The stationary half of the die that remains fixed during the casting process and the extraction of the final part.
- **Moving/Mobile Die**: The movable half of the die that opens to be able to extract the final solidified part.
- **Mold Cavity**: The hollow space between the fixed and moving die. It's the space that forms the casting when the molten metal is injected.
- **Ejection Pins**: The extraction components that push the final solidified casting out of the die when the moving die opens.
- **Shot Sleeve**: A tube where the molten metal is poured in from the furnace. It guides the metal into the mold cavity.
- **Plunger**: A cylindrical part that injects the molten metal into the mold cavity.

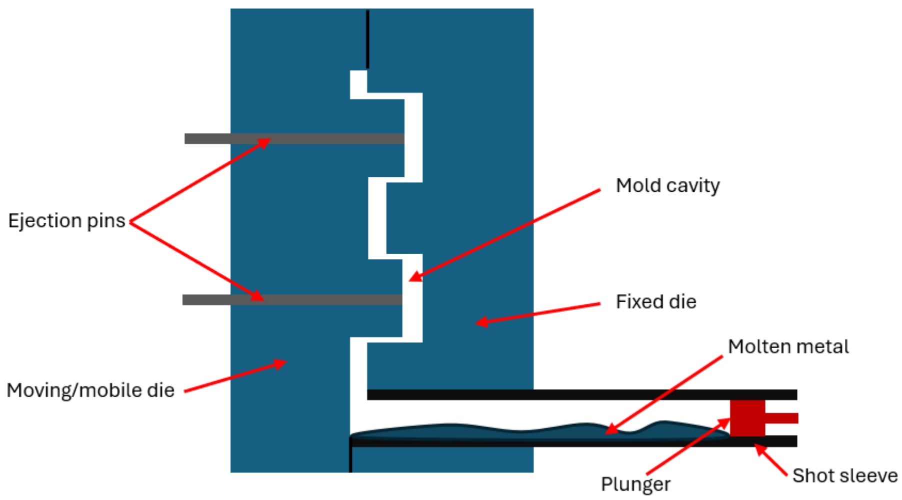


**Figure 2.1:** Simple sketch of a HPDC machine.

In the process of HPDC, several elements that are not intended and wanted in the final part need to be included in the casting design. These are additional and necessary elements of the casting to ensure the overall quality of the final part. For example, the gating system (runner and ingate) is a crucial part of the casting because it facilitates the flow into the mold cavity. Overflows are extra parts that capture air and gases and the biscuit is the leftover metal that solidifies in the shot sleeve. See figure 2.2

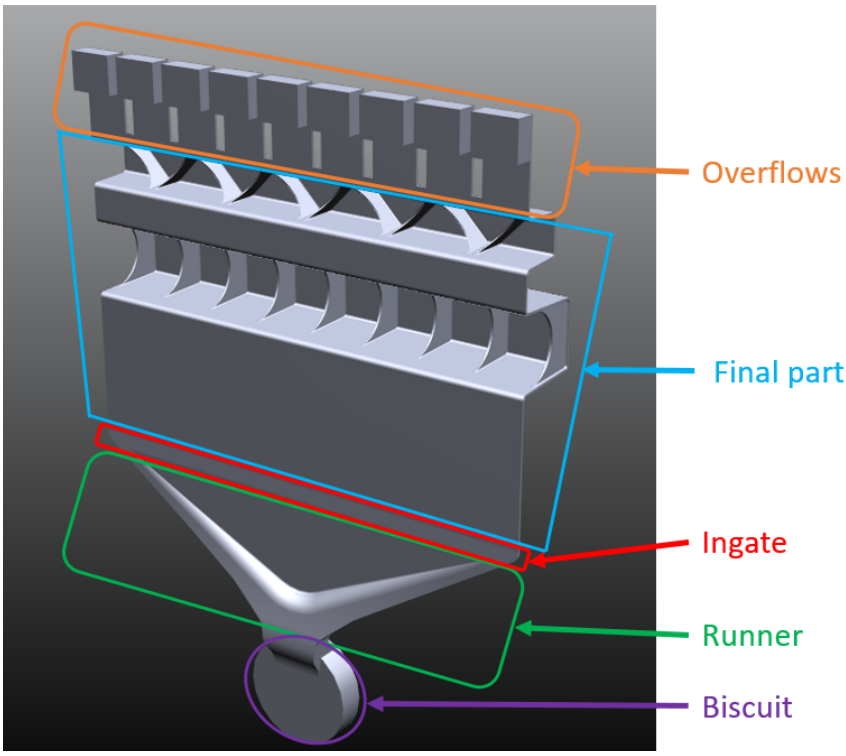


**Figure 2.2:** Representation of a casting and intended part in blue.

## 2.2 Overview of the High-Pressure Die Casting Process

High-pressure die casting is a manufacturing process used in multiple industrial fields. This type of manufacturing corresponds to approximately 50% of the world's production of lightweight parts [8]. Since the process of HPDC consists of several operations, it is considered a complex process. See figure 2.3 for a better understanding of the HPDC process steps.

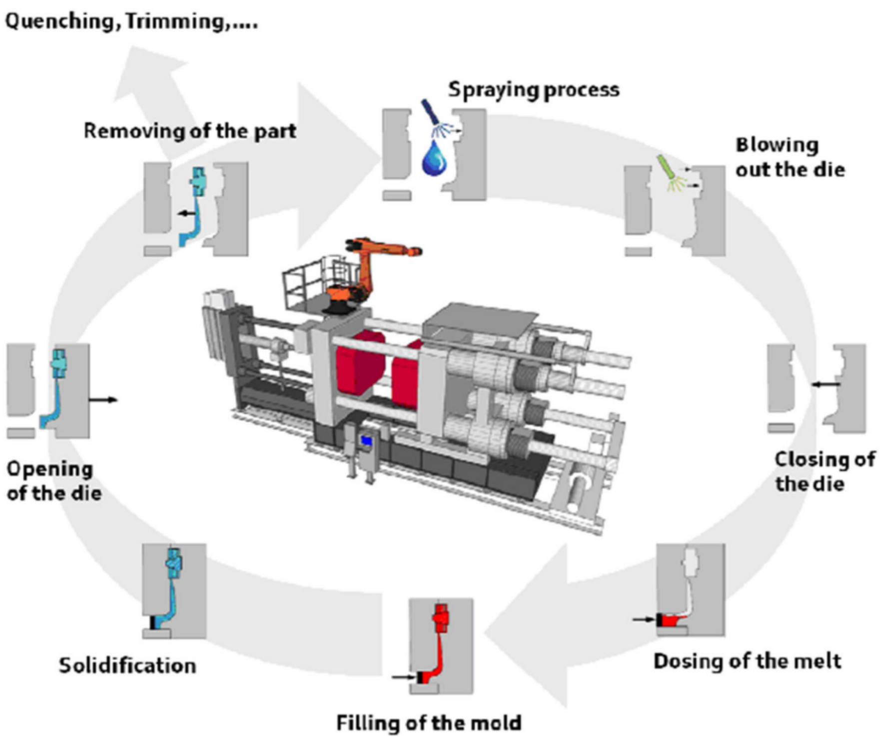


**Figure 2.3:** The Process chain of HPDC [8].

In HPDC, molten metal is poured into a shot sleeve for each cycle. A piston presses the molten metal with high pressure, resulting in high metal velocities (30 m/s - 60 m/s). When the mold is filled, the part/component will be cooled and when solidified extracted from the moving/mobile die. But before the injection of the molten metal, the dies need to be sprayed for the dies' safety [8].

HPDC has been used for over 100 years and was mainly used for zinc; today it has become a common way for mass production of light-weight components [9]. In the world of automotive, this process has become more common since there are several categories that it could be applied to, namely:

- Powertrain
- Interiors and electronics
- Chassis and body structure

The most demanding application in terms of mechanical properties, highest strengths and highest elongations, is the body structure since it needs to absorb large loads in case of a crash [9].

Generally, the complexity of a part is determined by multiple factors, such as weight, size, and geometry, but also its' deformation capabilities, and therefore parts of the body-structure could be classified as complex [9].

Quenching, also known as cooling, is a heat treatment step after ejection. It involves rapid cooling of the casting to room temperature by immersing it in different media such as water, or other media. There are other ways of quenching such as spray quenching or air quenching. According to [10], alloying elements disperse from the solution when it is slowly cooled. In addition, they start to concentrate at grain boundaries, small gaps, unassimilated particles, dislocations, and other "imperfections" in the aluminium lattice. In contrast, it's preferred to slow down the dispersion and keep the elements in the solid solution until the age-hardening step, to acquire corrosion resistance, ideal strength, and toughness [10]. In addition, after quenching, aging is done to create a fine distribution of elements and further enhance the strength of the material [10].

Trimming is a subsequent step following the quenching of the mega-casting [2]. It entails mechanical trimming to cut off unintended elements attached to the casting. But it's also a step where the geometrical quality could be affected due to the spring-back effect [2].

## 2.3 The Gating Design

The design of runners, gating systems, and venting systems determine the quality of HPDC parts. The most common designs of the runner systems are the vertical runner system, V-shaped runner system, and horizontal runner system [11]. In addition, in a large and thin-walled casting, avoiding distortion becomes more critical, due to the non-homogeneous heat transformation during mold filling [12]. This can potentially create an unfavorable solidification pattern which in turn causes the part to warp [11]. Furthermore, the contraction of the gating system during solidification can drag the other sections of the casting causing distortion and hot tearing [12].

For high-precision and compact parts, the V-shaped gating system is the most suitable. However, more amount of melt will be needed [11].

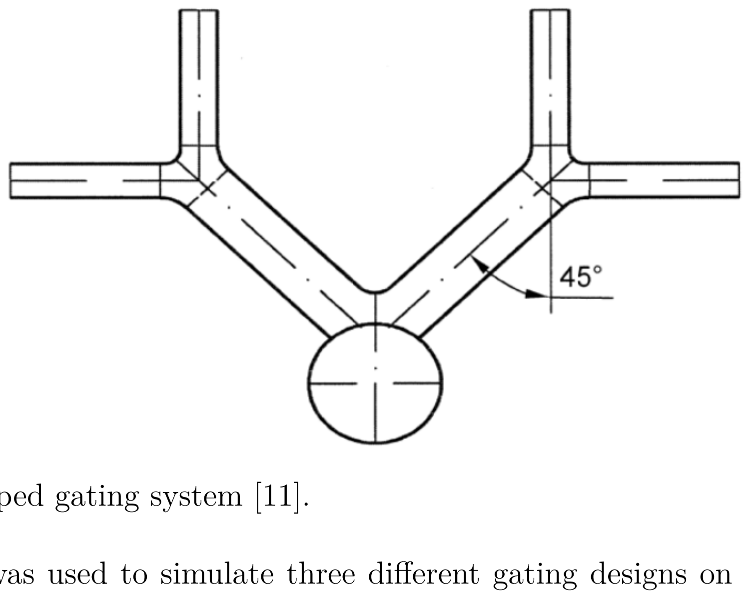


**Figure 2.4:** V-shaped gating system [11].

A FEM approach was used to simulate three different gating designs on a HPDC casted component [13]. Through these simulations, the authors analyzed the influence of the gating system on the quality of the castings. The different designs of the gating system showed different amounts and types of defects e.g. defects of simulation (A) are mainly related to porosities and entrapped gases. However, simulation (B) showed deformation-related defects, due to the uneven shrinkage stresses. Simulation (C) showed similar defects as simulation (A) but to a reduced extent, meaning the porosity and entrapped gas defect returned. See figure 2.5.

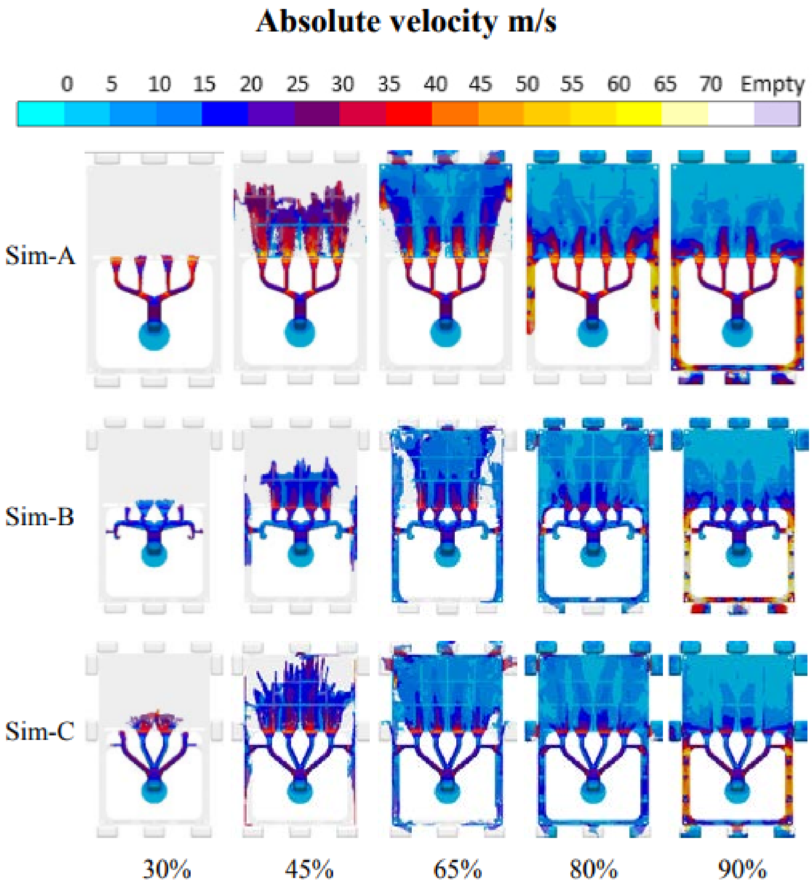


**Figure 2.5:** The filling percentage and absolute velocity for the different simulations[13].

A YouTube video by TMIO Tesla [1] provided a picture of the Tesla Giga press, see figure 2.6 (a). As it appears in the pictures, the notable difference between the Volvo mega-casting (a prototype) and the Tesla rear floor is the bar marked in red (a1) and the legs for the backend of the rear (a2).

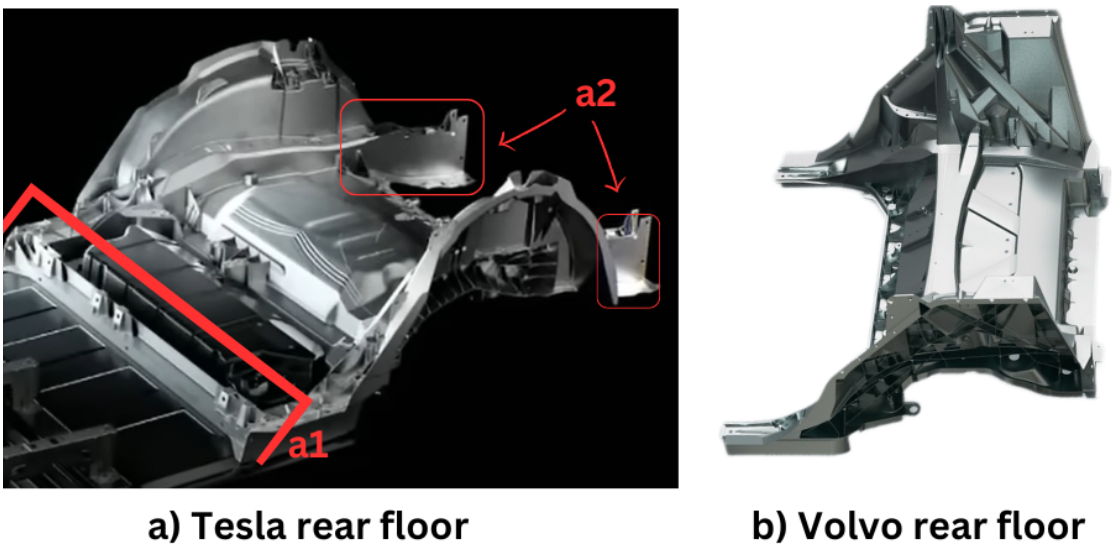


**Figure 2.6:** Teslas' and Volvos' mega-castings of the rear floor.

Another YouTube video by Tech Charge [2] shows the gating system of the same casting in figure 2.6 (a) marked in red. The Tesla mega-casting has a fan-like gating system and is connected to the backend of the casting, in between the legs. See figure 2.7.

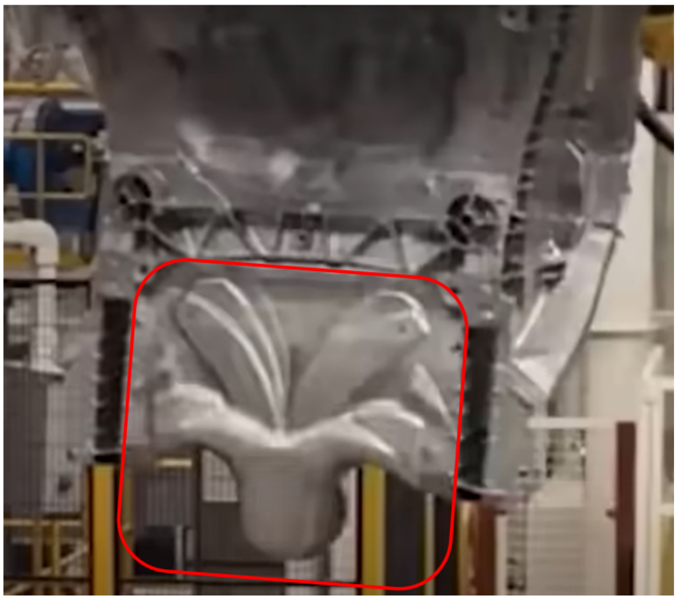

**Figure 2.7:** Teslas' gating design of their mega-casting.

[1] https://www.youtube.com/watch?v=uh0rx4A6qf8&t=115s
[2] https://www.youtube.com/watch?v=fydlvpDZrAw&t=124s

Another car manufacturer that adopted the mega-casting technology is the Chinese Xiaomi [3]. Xiaomi calls it "Hyper Casting" and their rear floor casting is quite similar to the Tesla casting. However, the design of the Xiaomi gating system (marked in red) is different. The Chinese producer has a fingers-like gating system which is also located at the backend of the casting, see figure 2.8.

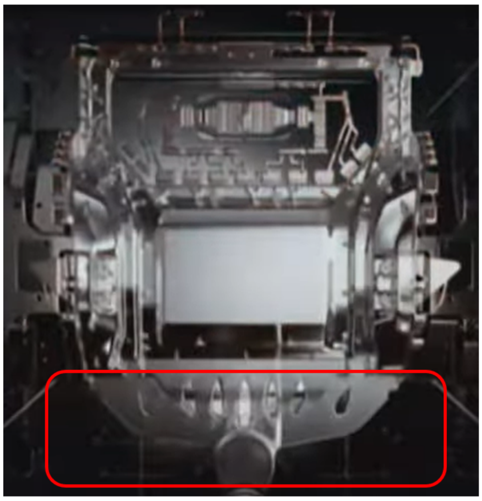

**Figure 2.8:** A whole mega-casting of the Xiaomi rear floor.

Another YouTube video [4] revealed the mega-casting of the Chinese manufacturer Zeekrs' rear floor. As shown in figure 2.9, the design of the gating system (marked in red) is different from the Tesla and Xiaomi mega-castings. The gating is placed in the middle of the casting as the biscuit is in the center of the floor. The melt seems to be distributed to the cavity through a finger-like gating design. However, unlike the above-mentioned rear floors, the Zeekr floor has no "free" front legs (red rectangles marked). The legs are completely united with a complete floor. Another important point to comprehend is that a massive gap will appear in the middle when the gating is removed by the trimming process.

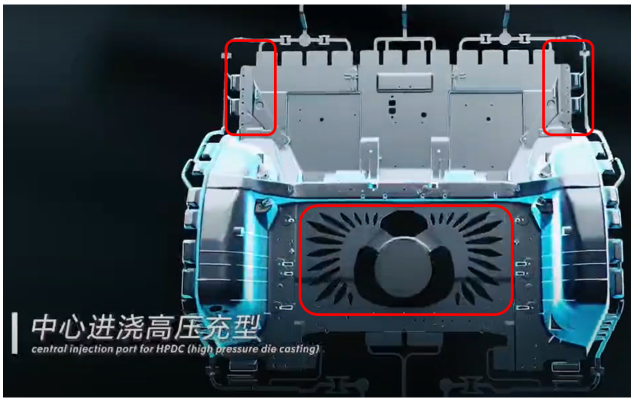


**Figure 2.9:** A whole mega-casting of the Zeekr rear floor.

[3]`https://www.youtube.com/watch?v=wRNRg_PXZe0`
[4]`https://www.youtube.com/watch?v=C8lZMQOkLwY`

## 2.4 Study Findings of Contributors to Geometrical Variations

The following section will discuss studies that examine different process parameters and residual stresses to highlight their impact on the distortion of HPDC castings.

### 2.4.1 Residual Stresses in HPDC

Residual stresses are internal stresses that are induced in HPDC without any external loads applied [14], [15]. These stresses are induced because the contraction is constrained due to different cooling rates within the casting and also because the casting is not free to move when it's locked in the mold. Another important factor that induces these stresses is the phase transformation during the cooling process. Furthermore, castings with larger stress gradients and complex stress distributions tend to vary the stress measurements [14].

Residual stresses are classified as primary and secondary stresses and the difference between them is that the primary stresses do not depend on the geometry of the part, whereas the secondary does. The primary stresses occur when the molten metal starts to solidify and cools in the mold. Secondary stresses occur when different parts of the casted component have different temperatures. The temperature difference between the two parts results in one side being under tensile stress and the other under compression, resulting in distortion in the final shape. The distortion is a result of plastic deformation when the tensile stresses exceed the elastic limit and the yield strength, and enter the plastic strain phase [16].

Residual stresses are also affected by the quenching process due to cooling differences between the surface area and the interior of the component. Thermal gradients will be induced which also affect the contraction of the casting. These gradients will disappear, though their impacts on the component will be perceptible in later stages. The uneven stress distribution is also a result of quenching and these quenching stresses are a significant contributor to component instability during the following post-processing operations e.g. machining. This often leads to geometric variation in the components while the component is in service [17]. The combination of residual stresses and high external stresses during the use phase often results in cracks in sensitive areas of the part [18].

### 2.4.2 Process Parameters

A study [16] was conducted to examine different process parameters in the casting process, e.g. die temperature and cooling regime, to analyze their effects on the distortion of the final casting shape. The study highlights that the different wall thicknesses may be the cause of residual stresses, which in turn cause distortions. With the presence of residual stresses, the ejection forces tend to cause distortions during the extraction of the casting from the die. Nonetheless, smaller defects, such as hot tears, porosities, blistering, or cold shuts, have a major effect on the castability of the part and thus have a significant impact on the geometry of the final shape [16]. Hot spots, sink marks, differential shrinkage, thermal residual stress,and warpage are example of quality defects of the casting that could be minimized by having an efficient cooling system that achieves a uniform temperature distribution [19].

Another numerical study [20] was conducted to reduce residual stresses and deformations of HPDC castings by testing several process parameters and establishing their relationship with the stresses. To obtain accurate results, the authors simulated the component using the commercial software AnyCasting, 3D scanned the casting, and compared the simulation results with the 3D scans. The results showed that filling, cooling/solidification, and ejection are process steps that lead to distortion in the final shape due to residual stresses. These stresses are a result of uneven cooling as well as non-uniform shrinkage [20].

The authors also claim that differences in wall thickness could cause differences in the temperature gradients and lead to stress differences, see figure 2.10 for a clearer description. These stress differences are the result of the thermal shrinkage differences between the thick and thin areas during the cooling phase. In such cases, the thinner parts of the component are exposed to compression, while the thicker parts are exposed to tension stress [20].

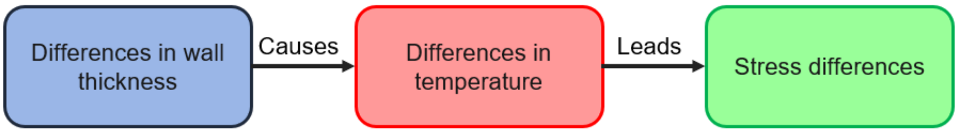


**Figure 2.10:** Simple flowchart describing the differences in three stages

Two different components - a stress lattice and a V-shaped component, see figure 2.11, were simulated in the MAGMAsoft tool, to minimize defects affecting the components' shape through optimizing the filling and solidification phases [16]. The results showed that differences in wall thickness are an important factor to consider since they affect the geometry of the part when cooled due to inhomogeneous cooling. Calculations to determine global distortion were also conducted using Hooke's law. The measurements are based on reference points before and after the cooling phase.

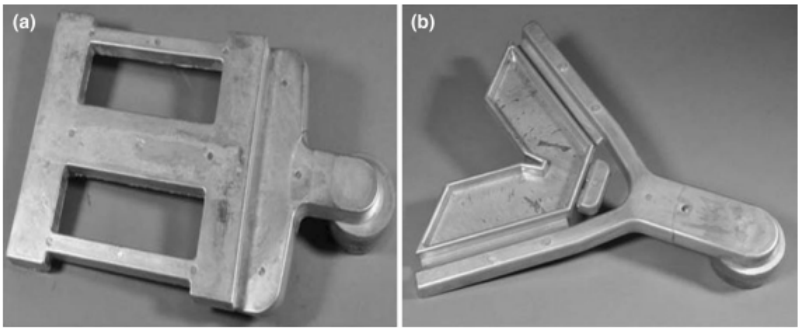


**Figure 2.11:** a) stress lattice, b) V-shaped component [16].

The results also showed that the quenching phase influences the geometrical accuracy of the stress lattice [16]. This is due to temperature differences between different parts of the stress lattice. However, the result showed that the die temperature had more of an effect on the V-shaped component. High die temperature combined with shorter time in the cavity results in higher temperatures during the ejection phase, potentially leading to plastic deformation due to lower yield strength. The authors' main conclusion is that the global distortion of a component also depends on its geometry and thickness [16].

Another study that investigated the distortions and residual stresses was conducted at the University of Jönköping in Sweden [21]. However, the experiment was based on magnesium alloy. The component tested is an engine crankcase of a chain saw. The process parameters studied were:

- (A) First-phase injection speed
- (B) Temperature of fixed half of the die
- (C) Cooling time
- (D) Intensification pressure

The authors investigated the best combination and the relationship between these parameters to obtain accurate and reliable results. To achieve this, a Design of Experiment (DoE) was conducted in the DesignExpert™software.

Different part thicknesses in the components could be the cause of non-uniform cooling, and for complex geometries, it could create plastic deformations [21]. Furthermore, large residual stresses with high temperatures could lead to permanent distortion when the stresses relax/rest. Therefore, finding an optimal set of parameters could provide high-quality castings and reduce the geometrical variations [21].

The results after applying Analysis of Variation (ANOVA) showed that an increase in the intensification pressure minimized the distortions at a certain point. The temperature of the fixed half of the die is also a significant parameter because it increases the total distortion and makes the part distort towards it. This also means that the temperature difference between the two halves of the die is an important factor. In addition, increasing the mobile die temperature reduces the residual stresses. The study also revealed that cooling time inside the die and first phase injection had less effect on the distortions and residual stresses [21].

Another study was conducted to meet geometric tolerances in HPDC castings [22]. According to the authors, the integrity of a casted component is influenced by a combination of the following parameters:

- Die temperature
- Filling phase
- Components' design complexity
- Cooling rates in the mold

They also claim that the die temperature, in-gate velocity, and casting pressure have a relation to the mechanical properties of the component. The intensification pressure is also an important factor for the production of high-integrity components as it reduces the porosities. Deformations of the casted component in combination with the porosity defects are major drawbacks of the HPDC process. This occurs during the cooling phase in the mold cavity due to plastic stretch, caused by natural shrinkage in the component, since it's locked between the dies and not free to move. This phenomenon contributes to the inducement of residual stresses and springbacks during the quenching phase [22]. The authors also mean that the porosity problem is a well-studied topic, while the deformations remain.

An additional study investigated the effect of mold and pouring temperature on the hardness and microstructure of a HPDC hyper-eutectic aluminium alloy (AlSi17Cu4) [23]. The study concluded that in order to get good quality, the pouring temperature should range between 720 and 750 degrees together with preheating the die between 126 and 130 degrees. It also concluded that extremely high or too low pouring temperature impacts the allocation of the primary silicon and the mechanical properties such as hardness and density.

### 2.4.3 Extra-large Thin-walled HPDC Castings

A common feature in HPDC components is thin-walled castings due to economical as well as weight savings reasons. This common feature is a contributor to distortions in castings [22]

Effective Flow Length (EFL) is an approach introduced in a study [24] that asses the castability and the quality of extra-large thin-walled HPDC castings (Aluminium alloy). The flow length is the maximum distance that molten metal can travel in a die. The studied and simulated component is shown in figure 2.12. Several tests on different process parameters were conducted to study their relationship and assess the quality of the final shape. Some of the parameters were the die temperature, melt temperature, and cavity fill time (which corresponds to the in-gate velocity).

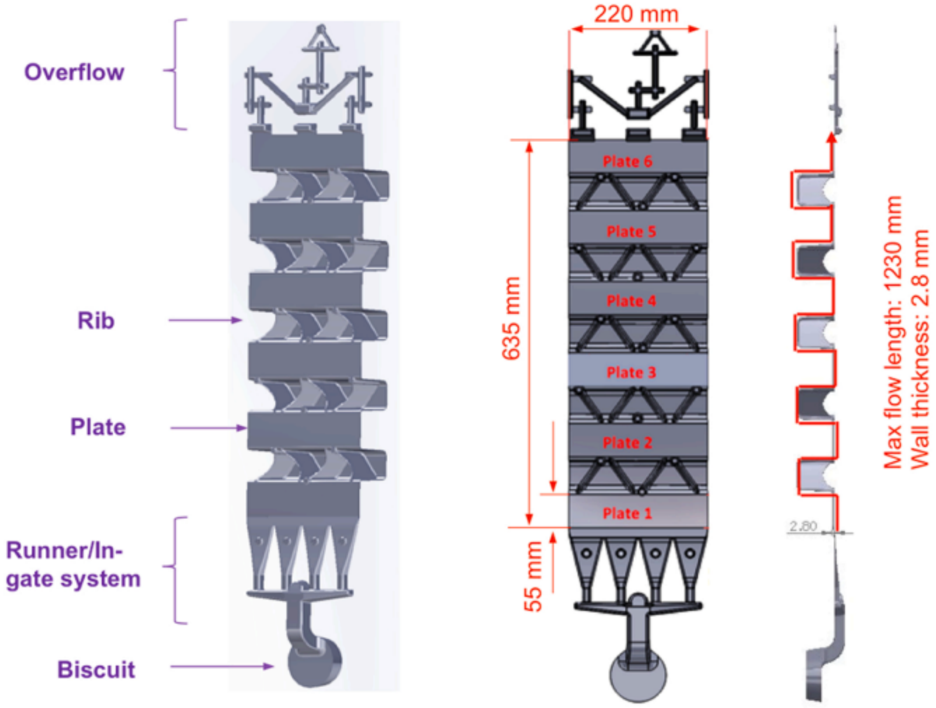


**Figure 2.12:** Representation of the extra-large thin-walled casting [24].

The in-gate system and the overflows for the studied component were optimized in design as well as for the heating channels, vacuum system, and spraying control. After running a test with the die temperature at 200 C, melt temperature of 720 C and cavity fill time of 41.1 ms (which correspond to an in-gate speed of 50 m/s), the results showed that it is more likely that the molten metal will solidify before reaching the overflows due to a decreased temperature, see figure 2.13. Such differences in the solidification phase could affect the castability of the component since it could affect the mechanical properties [24].

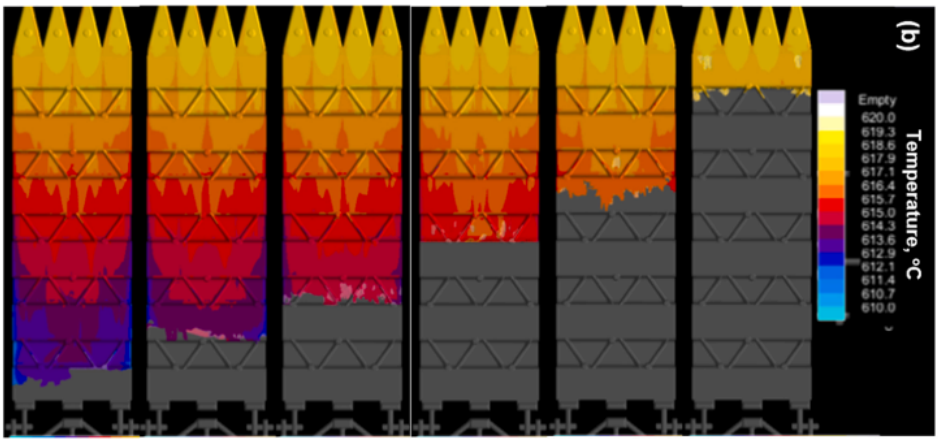


**Figure 2.13:** A representation of how temperature decreases throughout different stages of the filling process [24].

Regarding the topic of extra-large thin-wall castings (in this case-study 2.8 mm thickness), there is a combination of process parameters that affects the fluidity of the molten metal into the mold cavity which in turn affects the castability and the final quality of the casted part. The results were obtained from a similar study of a DoE where multiple values of the parameters were tested.

The idea behind the EFL is to detect quality concerns by measuring the distance a molten metal has traveled inside a die before it solidifies. If it is less than the EFL, it indicates that the molten metal didn't reach the overflows, and the cast part is defective. This is because the overflows can capture dirty melt and air entrapment and thus are important areas to consider. Therefore, one of the authors' important highlights is that the in-gate velocity is an essential factor for the castability of extra-large thin-wall castings [24]. However, the study continued with another experiment where the relative in-gate velocity was tested again, but with a higher temperature of the molten metal to assess the castability as well as the combination between the in-gate velocity, the temperature of the melt, and the die temperature. The results were still almost the same, which indicates that the velocity still needs to be high relative to the temperature of the die and the melt. To elaborate, increasing the melt temperature and die temperature together with higher ingate velocity had similar results.

Moreover, the authors also claimed that defects such as cracks, misruns, surface flaws, and casting integrity are considered as important to study since castability refers to good finishing as well as the accuracy of the geometry.

The heat loss of the molten metal during the filling process could cause premature freezing as well as incomplete castings. Because of this phenomenon, fast accelerated filling becomes an important factor for thin-walled castings since it could prevent such defects. To prevent this premature freezing, superheating the molten metal could be a solution because it improves the fluidity. However, this approach introduces other problems, such as gas-porosities [12].

### 2.4.4 Insights from MAGMA Simulation Runs

MAGMA Foundry Technologies, Inc. has uploaded a short video on Linkedin [5] that reveals a simulation result of the displacement of a mega-casting, a rear floor. The result shows the distortion that the mega-casting undergoes during the whole process chain of HPDC (solidification, cooling, and trimming). The result shown in figure 2.14 is magnified to make the distortion more visible.

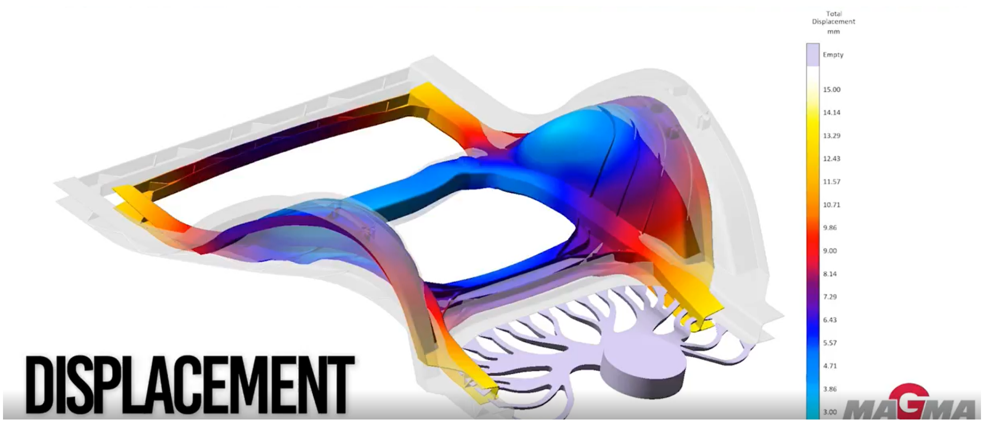


**Figure 2.14:** Displacement results for a rear floor mega-casting.

Another video that MAGMA has published is the temperature reduction the molten metal undergoes during the filling process, see figure 2.15

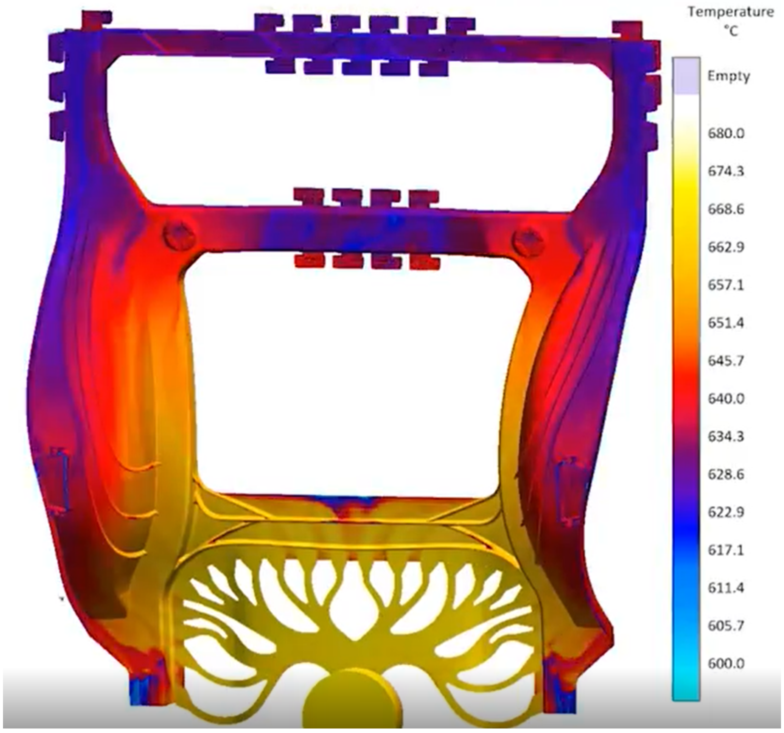


**Figure 2.15:** Temperature results for a rear floor mega-casting.

[5] https://www.linkedin.com/company/magma-foundry-technologies-inc./posts/?feedView=all

### 2.4.5 Vacuum Assisted Casting

One common defect in the process of HPDC is the air and gas entrapments in the melt when injected into the mold cavity. Experiments were conducted to compare the mechanical properties of aluminium castings using conventional HPDC and super vacuum-assisted HPDC. The process of using vacuum-assisted HPDC involves evacuating air from the mold cavity and the shot sleeve. This evacuation of air seems to reduce porosities in the alloy and result in improved repeatability of the properties. Moreover, the ductility was also improved and the fluctuations of it were reduced [25]. The tensile strength was also enhanced. The study showed that the usage of super vacuum-assisted HPDC provides improved repeatability with enhanced mechanical properties through a more uniform stress distribution. Fewer porosities also mean that cracks will be reduced, and with a vacuum, the process will produce high-quality die castings.

### 2.4.6 Soldering at the Ejection Phase

The ejection phase is the removal of the part from the die when it has solidified and cooled down. Since the part shrinks onto the die, ejection forces in the form of pins are used to push out the part [26]. Before locating the ejection pins, the forces should be predicted for each pin in order to prevent casting warpage. However, it's still important to release the casting smoothly from the die [27].

One common defect during the ejection phase is the soldering effect. Soldering is the sticking of the casting to the die and this defect often occurs in the hotter areas of the die [28], [29]. This problem causes surface damage to the casting, leads to dimensional defects [28], and increases the production downtime [29].

The general idea and assumption is that an increased interface temperature between the mold and the casting would contribute to an intermetallic layer. Intermetallic layers are chemical compounds formed between the die and the casting alloy and cause soldering, see figure 2.16. This means the traditional point of view of the soldering problem is through a thermodynamic and kinetic perspective [28]. However, in industrial practices, the soldering could start much faster than the thermodynamical models predict, due to the growth rates of these layers.

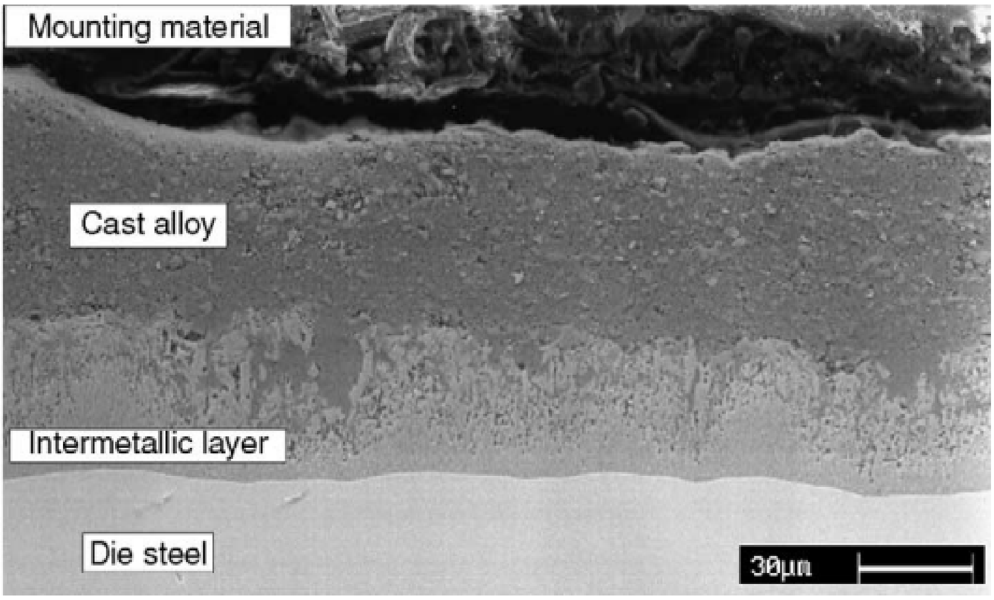


**Figure 2.16:** Cross-section that shows the soldering intermetallic layer [29].

A suggestion is to study and understand the mechanical interactions like galling, which is believed to have a major impact on the soldering effect because it's a wear process caused by sticking between sliding surfaces [28]. The point is that to mitigate the soldering effect during the ejection phase, a broader study should be conducted to apprehend the mechanical interactions and not only the chemical and the thermal ones.

It is also shown that aluminium alloys with silicon content tend to reduce the soldering problem and the growth of these problematic layers. This means that increasing the silicon content in the aluminium alloy decreases intermetallic layers' growth and thus minimizes the sticking effect [30].

Another important factor that reduces the soldering phenomena is the lubrication of the mold before injecting the molten metal [31]. Since the lubrication acts as a mold release agent (MRA), it creates a protective layer between the die surface and the actual casting. In addition, the MRA improves the fluidity during the filling, facilitates the ejection of the casting, and reduces the unbalanced die temperature [31].

### 2.4.7 Alloy Composition

Although the trend of mega-casting and Giga press has been shown in recent years, a book from 2012 [9] did discuss the idea of larger castings and specifically discusses the HPDC process for automotive parts. A chapter also discusses the alloy compositions for such automotive applications.

The BMW Series 5 GT rear lid is shown in figure 2.17. According to the authors, the dimensions of the casting are accurate for a 3 mm thick walled casting. One of the requirements for this larger casting is the long-term crash properties and this is fulfilled by an aluminium casting which also allows a great deal of design-freedom than steel alloys.

**Figure 2.17:** The GT models' lid frame. Weight: 11.6 kg. Dimensions: ca. 1230 x 1250 x 390 mm [9].

Another part that was discussed in the chapter is an integral crossbeam, also for a BMW car, see figure 2.18. The authors' claim is that the quenching phase would cause a distortion of the arms [9]. This geometrical variation in the final shape does not meet the requirements for high dimensional accuracy and would therefore be unsuitable to use. What makes it unfit for usage is that aluminium casting is welded to the rest of the chassis at several points [9].

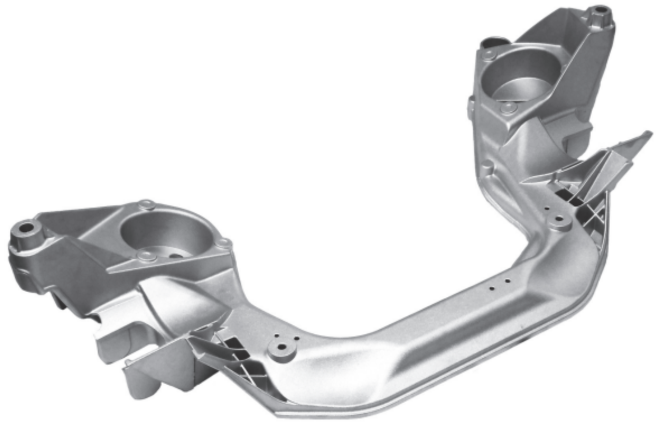

**Figure 2.18:** BMWs' cross beam. Weight: 4.1 kg. Dimensions: ca. 810 x 450 x 210 mm [9].

The continuation of casting larger components with complex designs makes the traditional AlMg alloys difficult to use due to poor flowability. However, by adding silicon to the alloy (AlSiMg) the flowability would be improved [9]. This means that the alloy composition is also an important factor to consider for producing accurate die-castings. One of the most important elements for die-casting alloys is silicon since it improves the castability, fluidity, and hot tear resistance [7]. With subsequent quenching, the desired properties could be achieved. However, solution heat treatment would be a problematic process due increased risk of distortions [9]. Silicon is also responsible for low shrinkage, and low density which is beneficial in the weight reduction of products[32]. Increasing silicon content also increases the ultimate tensile strength [32].

Another part mentioned in the chapter is Audis' rear connector for the A8 model, see figure 2.19. This component is relatively long compared to the other mentioned castings, 1.45 m long, and weighs 10.2 kg. Reinforcements in the form of ribs need to be strategically located to balance the weight, and this is done by mapping the loads [9].

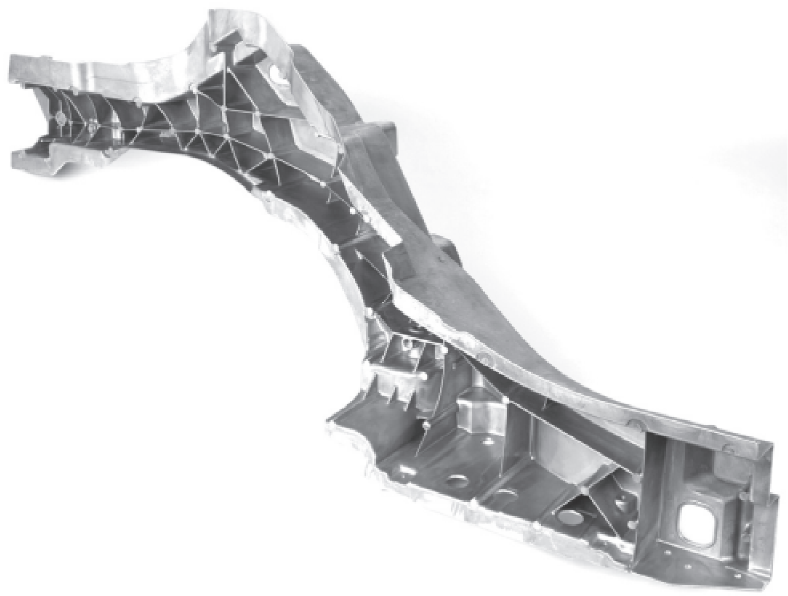

**Figure 2.19:** Audis' rear connector. Weight: 9.9 kg. Dimensions: ca. 1454 x 375 x 552 mm [9].

## 2.5 Quenching

Strength, ductility, and thermal stresses are examples of material properties that are affected by the cooling process of age-hardenable aluminium alloys. Thermal residual stresses are closely related to the uneven temperature distribution within the metal [18]. Reducing the cooling rate from solution heat treatment minimizes thermal stress [10]. However, solute atmos diffuse to grain boundaries and disordered regions when the quenching rate is not rapid and thus provides no enhanced strength during age hardening [33]. On the other hand, the rapid cooling rate increases the risk for distortion [10] and residual stresses[33]. Thus, optimizing quench parameters and minimizing the unwanted deformation becomes the main challenge in quench setup [10]. The most significant factor controlling the cooling rate is the media temperature [34].

Generally, the hardness of the as-quenched, which is the part after being quenched, is enhanced with higher cooling rates. The enhanced hardness is due to solute elements locked in the solution at a high cooling rate. With decreasing cooling rates and lower homogenization temperature, the tendency to form non-hardenable precipitates or in other words, "Quench Sensitivity" increases. [10].

A metal sheet of aluminium alloy (AA6082) with dimensions of 20x20x2 mm was quenched in different media. Figure 2.25 shows the cooling curves for different media with different start temperatures. It also indicates the cooling rate e.g. still water has the highest cooling rate while cooling in still air has the lowest cooling rate. [10].

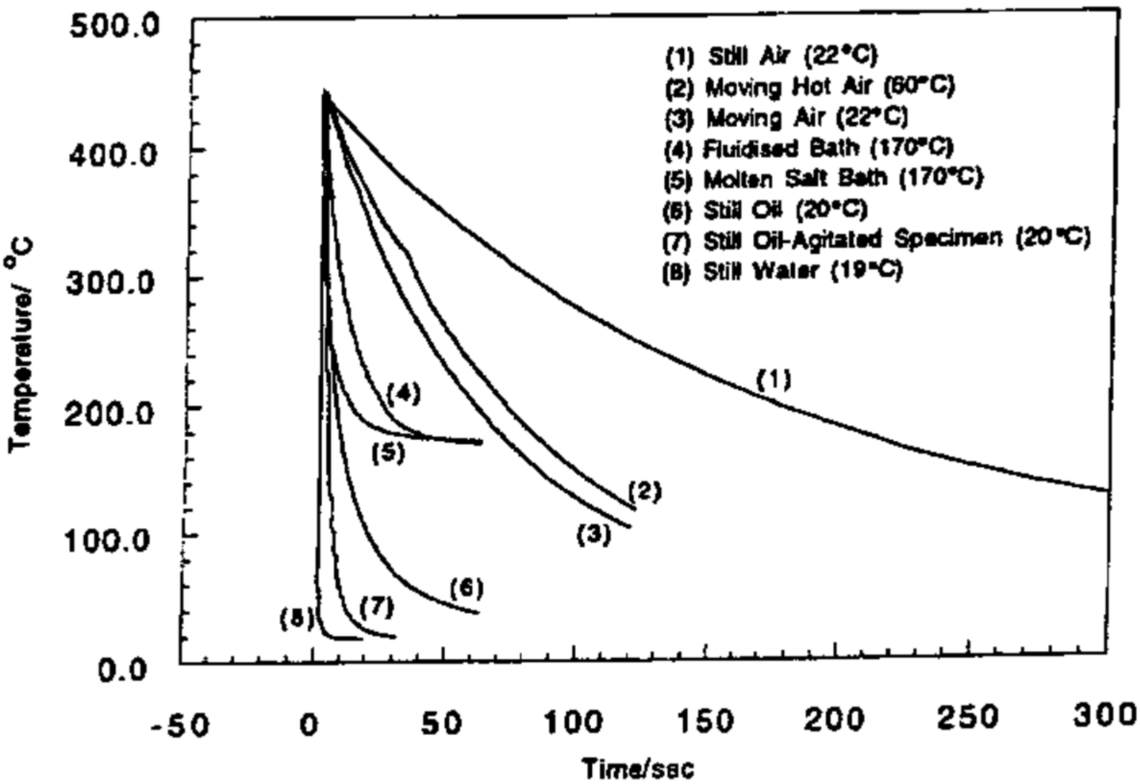


**Figure 2.20:** Cooling curves for AA6082 alumnium sheet quenched in different medias [10].

.

### 2.5.1 Quenching Mechanism

Generally, when a hot casted part is immersed into a liquid quenchant, the heat transfer undergoes three different phases/stages [35].

1. A stage: Vapor phase
2. B stage: Boiling phase
3. C stage: Convection phase

Film boiling is known as the initial and the relatively slow step because the hot surface gets enclosed by a vapor blanket, which slows the cooling process[10]. During this step heat is mainly transferred by radiation [33]. The vapor blanket is very steady and has an effect on the creation of surface soft spots [33].

The vapor blanket breaks as the part cools [10]. Nucleate boiling is the second stage and it starts after the breakage of the vapor coat [10]. The temperature separating film boiling and nucleate boiling is called "Leidenfrost temperature." During nucleate boiling the heat transfer is fastest, the heat transfer coefficient, $\alpha$, for film boiling, is 100x lower compared to $\alpha$ during nucleate boiling [10]
.
The last stage is the convection cooling during this stage the heat is transferred from the quenched part to the liquid by convection [33]. It is also influenced by factors such as the specific heat, thermal conductivity, and temperature difference between the quenchant and quenched part. In addition, it is usually known as the stage where most distortion arises and the stage with the least efficient stage of three stages [33].

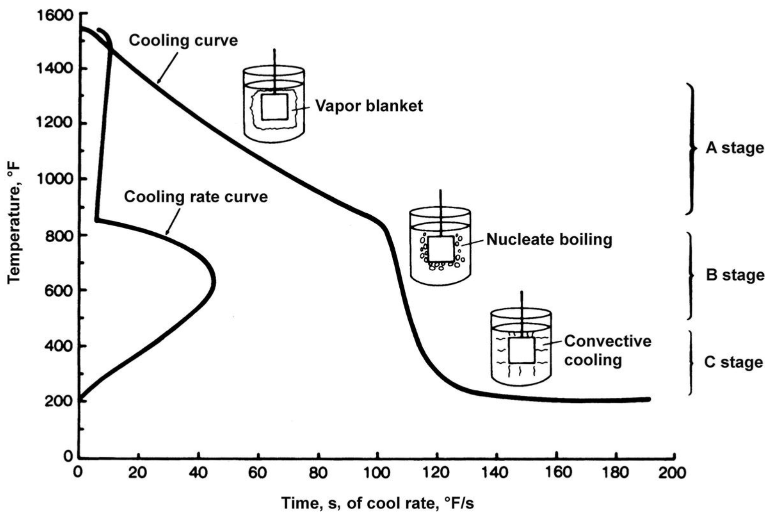


**Figure 2.21:** Immersion quenching and its cooling stages and mechanisms [35].

### 2.5.2 Cooling Rates and Quench Severity

The cooling rate is influenced by multiple elements [33]:

1. Type of Quenchant:
    - Water
    - Air
    - Polymer
    - Liquid nitrogen
2. Quenching Techniques:
    - Immersion
    - Spray
    - Still air
    - Air jet
3. Material Properties and workpiece characteristics :
    - Thickness
    - Design
    - Surface quality
    - Workpiece's internal characteristics affecting heat transfer to the surface

The quench severity is dependent on several factors such as:
- Development of vapor blanket
- Boiling properties
- Velocity of the fluid
- Tempreture of fluid
- Specific heat of the fluid
- Heat of vaporization
- Conductivity
- density
- viscosity
- Wetting properties of the fluid

### 2.5.3 Quenching Media

### Water

Water is the most commonly used fluid for quenching aluminium alloys. In addition, it has many benefits such as inflammability, cost-effectiveness, non-hazardous, and easy filtration. But it also has drawbacks with the residual stresses and distortion because the rapid cooling rate is achieved at the lower temperature ranges. Another drawback is that it could give a long vapor blanket stage depending on part complexity and water temperature [33] see figure 2.22. Film boiling is expected at the first stage when quenching the aluminium solution into water. Because the heat treatment temperature of the aluminium solution is notably higher than the Leidenfrost temperature [10]. Stable wetting and nucleate boiling will occur at surface areas where the surface temperature is less than the Leidenfrost temperature [10]. The existence of different boiling phases on a workpiece with different heat transfer coefficients of factor 100 creates unequal quenching. Furthermore, this will significantly impact the wetting procedures and lead to notable thermal gradients and amplified distortion during quenching[10]. Increasing the water temperature stabilizes the boiling mechanism. Figure 2.22 illustrated how water temperatures above 54° [10]. Several factors need to be monitored to get repeatable quench results such as the temperature, agitation, and contamination because they affect the vapor blanket formation and heat transfer [33].

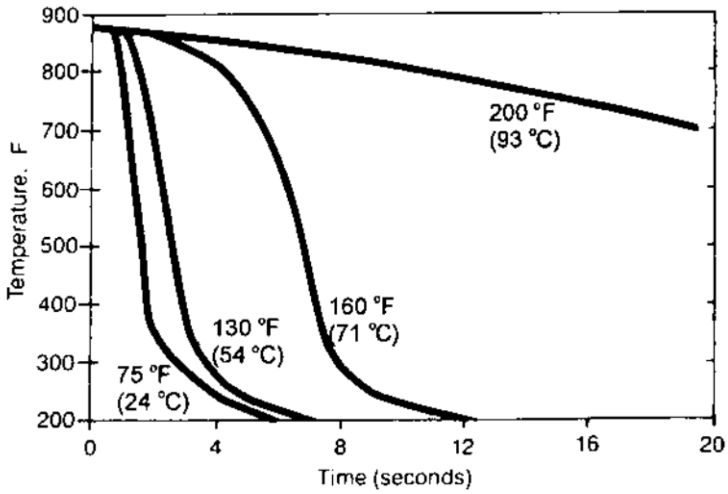


**Figure 2.22:** Cooling curves as a function of water temperature for 1/2 in. 7075 aluminium platec [10].

The non-uniformity of cooling comes with consequences: [[10],[36],[37]].

- Zones where film boiling (slow cooling) endures have more precipitate formation compared to zones with rapid cooling. During age-hardening, zones with slow cooling encounter a slight increase in hardness but in contrast, have a higher risk of intergranular corrosion than zones with a faster cooling rate [10].

- Zones where film boiling prevails during quenching have much lower yield strength compared to zones with marginal film phases. The uneven cooling process introduces thermal stresses that will lead to notable plastic deformation and increased distortion [10].

Quenching aluminium alloys in cold water may produce undesirable distortions as a result of the high thermal gradients [10]. One solution for this was delay quenching, which means quenching the aluminium alloy in boiling water and then immersing it into cold water at a suitable time [10]. Another solution is "*hot water quenching*" (60-71 °C) if distortion challenges arise with cold water (10-32 °C) [10]. Figure 2.23 shows how tensile strength varies with water temperature.

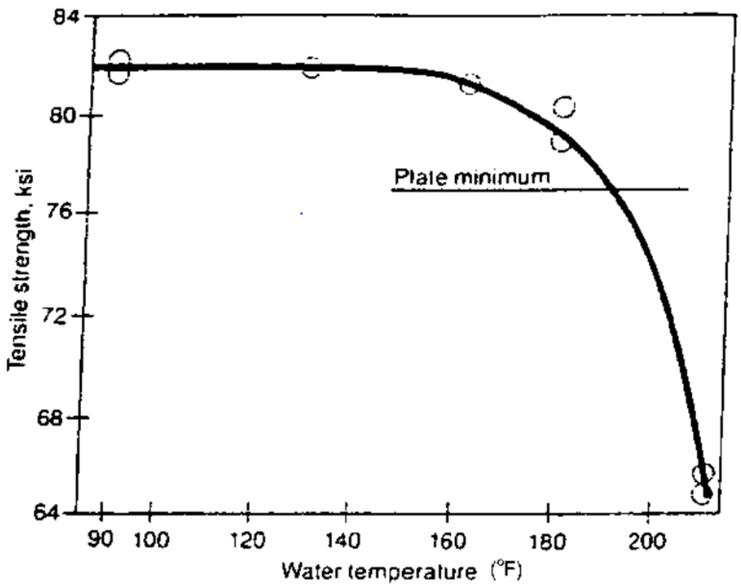


**Figure 2.23:** Tensile strength of 1 in. 7075 aluminium plate as a function of water temperature [10].

Generally, the highest strength obtained from age hardening is linked with quick quenching rates. However, a maximum quenching rate is not always the selected option, because it's accompanied by both residual stress and distortions [33]. Typically, the cost for optimum attainable properties is elevated residual stresses or distortions. On the other hand, low residual stresses and distortions are attained at the expense of properties [33].

In the majority of instances, distortion arises due to the severity of the quenching process. However, there are other critical factors. One of them is the racking. In order to control distortion in the furnace and quenching process a suitable racking becomes a very critical factor. The reason for this is:

- However, it's not only about enlargement, if parts are constrained and prevented from expanding or contracting evenly this will create substantial residual stresses or distortion. In addition, fixtures and the part have different expansion characteristics and therefore a careful plan needs to be made to prevent the different expansion characteristics because this will result in high levels of residual stresses and cause geometrical variation.

- Racking Orientation: the orientation of quenching the part after heat treatment has a direct impact on the degree and type of warpage. Different racking orientations such as horizontal, vertical, or angular lead to different types of warpage. Parts that are racked in a horizontal orientation tend to bow, however, parts that are racked vertically are susceptible to twisting if the mass is adequate.

- The configuration is the deciding factor for how fast the immersion will be. Usually, a slower immersion is used. However, some configurations are not dependent on how well-designed the racking is due to the existence of surfaces preventing the quenchant from reaching all areas, in such cases a slower immersion rate is applicable.

- Condition of the basket, racks, or fixture: Distorted parts result from distorted baskets, racks, and fixtures.

### Polymer Quenchants

For many years, hot water quenching has been utilized to reduce quench distortion in aluminium, but the severe distortion was not eliminated [10]. Quenching in water doesn't uniformly wet the surface of aluminium. In addition, nonuniform wetting creates different regimes with different heat transfer resulting in enough thermal strain to distort the part [10]. Furthermore, this resulted in the adaption of a new quenchant, aqueous poly (alkylene glycol)-PAG copolymer solution. It improves the wetting uniformity and creates a film around the quenched part that transfers heat. Polymer quenchants are water-based solutions, containing a polyalkylene glycol copolymer and additives that prevent corrosion [10]. Figure 2.24 illustrates the benefits of using PAG quenchants compared to both cold and hot water quenching.

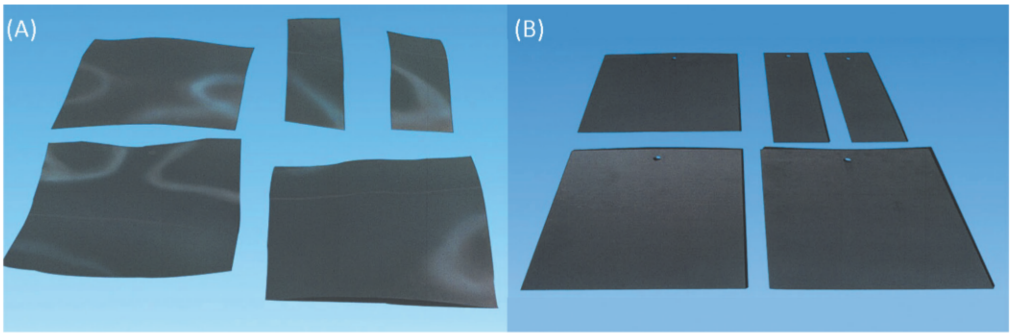


**Figure 2.24:** Comparison of water quenching and PAG 20 percent polymer quenching and its impact on distortion for a plate with 1.5 mm thickness. Upper left panel is 300×250 mm; Upper right panel is 100 mm×300 mm; lower left and right panels are 300×300 mm [34]

## 2.5.4 Spray Quenching

Spray quenching (SQ) is a technique that could range from heavy to fog spray depending on the application. It's usually for long parts, plates, sheets, structural shapes, and extruded parts. The advantage of using SQ is the intense quenching because it eliminates steam pockets. But it also requires careful planning and setup of the nozzles, their number, and location to create a uniform cooling that could prevent unfavorable distortion problems. In addition, there are two ways to control the quench rate in spray quenching. The first is the velocity of the water, the second controlling factor is the volume of water per unit area per unit time of the interference between the water and the workpiece [33].

### 2.5.5 Study on Different Quenching Types and Rates

A study [38] investigated the effect of different cooling rates on microstructure, residual stresses development and mechanical properties for high vacuum die casting AlSi10MgMn alloy. The different tests were based on SQ, air cooling (AC), wind cooling (WC), and water quenching (WQ). The SQ had three tests with different nozzle distances, air pressures, and water pressures see figure 2.26.

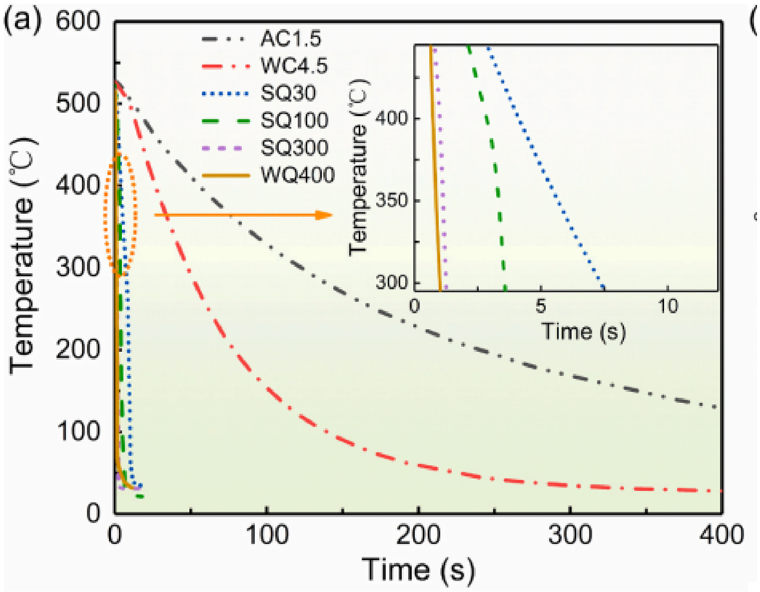


**Figure 2.25:** cooling curves at each quenching condition [38].

The parameters of the investigated quenching conditions.

| Sample | Quenching media | Water pressure (MPa) | Water flow (L/min) | Water temperature (°C) | Air pressure (MPa) | Air flow (L/min) | Distance (mm) | Cooling rate (°C/s) |
|---|---|---|---|---|---|---|---|---|
| SQ30 | spray | 0.2 | 1.4 | 25 | 0.5 | 5 | 170 | 30 ± 2 |
| SQ100 | spray | 0.4 | 1.4 | 25 | 0.3 | 5 | 170 | 100 ± 7 |
| SQ300 | spray | 0.3 | 1.4 | 25 | 0.3 | 5 | 80 | 300 ± 10 |
| AC1.5 | air | - | - | - | - | - | - | 1.5 ± 0.1 |
| WC4.5 | wind | - | - | - | - | - | - | 4.5 ± 0.3 |
| WQ400 | 25 °C water | - | - | - | - | - | - | 400 ± 10 |

**Figure 2.26:** The parameters of the investigated quenching conditions [38].

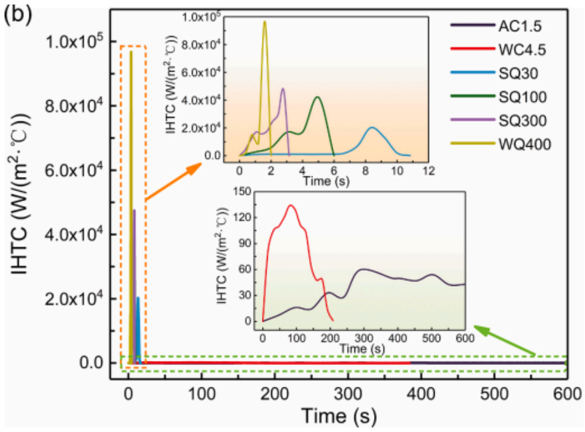


**Figure 2.27:** calculated IHTC curves for different quenching methods [38].

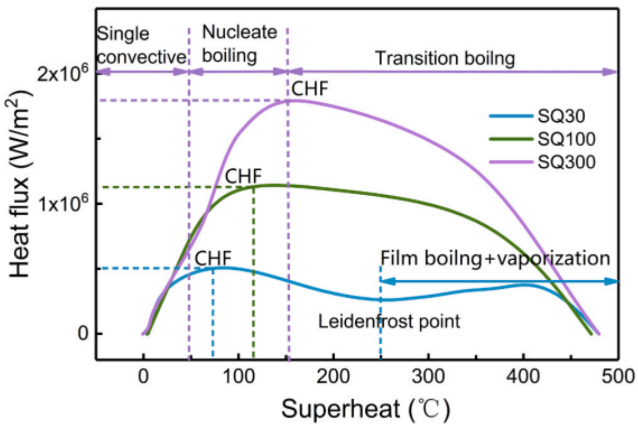


**Figure 2.28:** Boiling curves with different spray quenching parameters [38].

According to figure 2.27, the WQ had the highest interfacial heat transfer coefficient (IHTC) compared to the other quenching methods. It can be seen in figure 2.28 that SQ30 had a film boiling phase, unlike SQ100 and SQ300 which didn't experience it. They had transition boiling which is a phase where vapor film is very unstable and collapses constantly due to the different heat transfer between droplets and contact area. SQ30 resulted in small and spread-out droplets because it had the highest air pressure of 0.5 MPa and the lowest water pressure of 0.2 MPa. The small droplets resulted in the formation of vapor film because there was no major decrease in temperature when they touched the surface. In addition, the film could prevent the other droplets from reaching the surface and extracting heat which resulted in lower IHTC. However other factors such as the long distance between the nozzle and workpiece (170 mm) resulted in low droplet speed and weak impact on the vapor film. In contrast, SQ100 and SQ300 had better heat transfer and reduced surface temperature drastically see figure 2.27. Because they had high to medium-high water pressure (0.3-0.4 MPa) and a shorter distance between the workpiece and nozzle (80 mm) 2.26. In addition, it resulted in no film boiling in SQ300 and SQ100 see figure 2.28.

The high cooling rate (SQ100, SQ300, WQ400) resulted in high density and small Beta" precipitates which also gave high tensile strength and hardness and residual stresses. In addition, it resulted in narrower precipitate-free zones (PFZ).

The low cooling rate AC1.5, WC4.5, resulted in wider PFZ, the presence of Beta' and Beta' precipitates, and resulted in weaker material properties.

The study showed that a cooling rate at 30 C/s provided the wanted mechanical properties which is 85 percent of the ultimate tensile stress (UTS) of as-cast alloy. Because the part will be aged and more strength will be acquired. It also showed that the residual stresses, yield stress (YS), and UTS increased with the increase in the cooling rate. It also showed that elongation decreased with the increase in cooling rate.

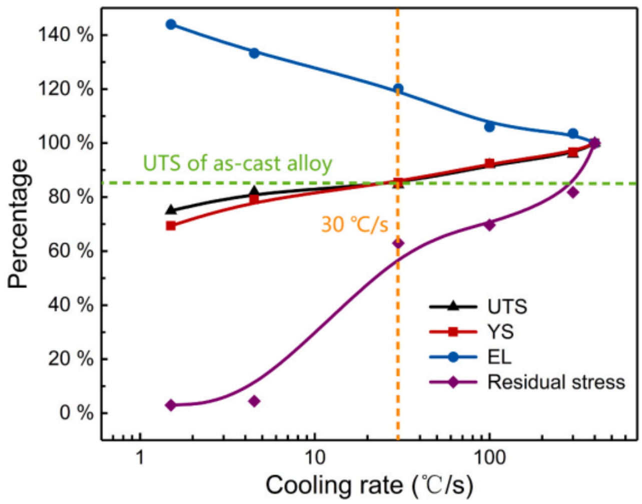


**Figure 2.29:** Comparison of the mechanical properties and residual stress of the alloys with different quenching cooling rates [38].

### 2.5.6 Quenching Orientation

A CFD study [18] investigated the effect of orientation by simulating six different orientations of an aluminium cylinder head quenched in water. It can be seen in figure 2.31 that joint face (JF) orientation has the highest vapor entrapment. However this didn't impact the cooling curves, figure 2.32 showed that the cooling curves are almost identical. Figure 2.33 shows that orientation has little impact on the overall cooling characteristics. However, its effect is localized in specific locations. Another important observation is that the duration of peak temperature gradient lasts for 15 seconds and in these 15 seconds metal could exceed yielding stress and plastic deformation begins, see figure 2.33. Another study [39] on AlSi 4340 steel found a strong correlation between different quenching parameters quenching orientation, heat extraction speed, type of quenchant, and geometry of the part. The highest distortion values were related to horizontal water quenching, while the lowest distortion values were connected to oil quenching with vertical orientation [39].

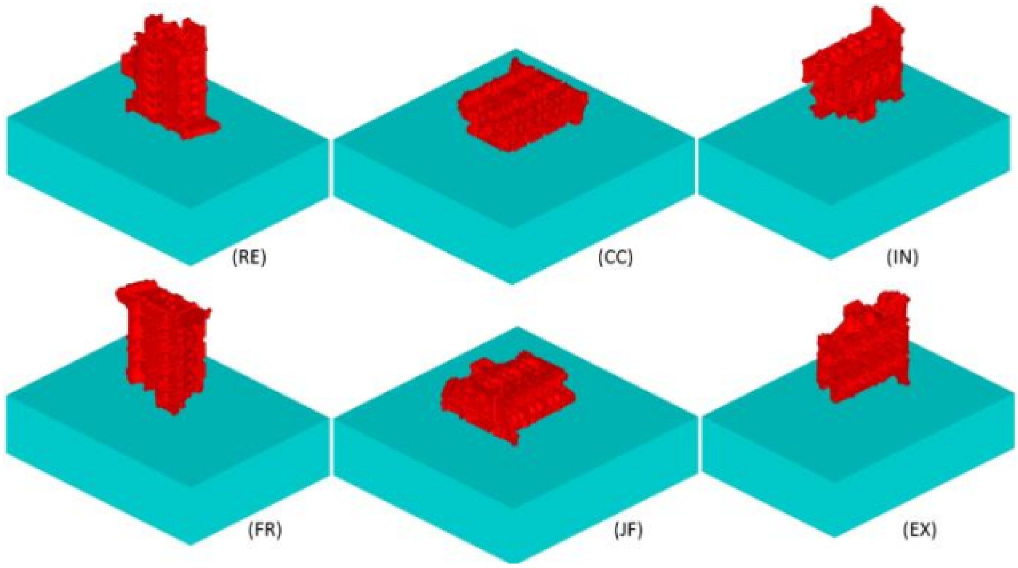


**Figure 2.30:** Water quench orientations: RE - rear face up, CC - cover face up, IN - intake port up, FR - front face up, JF - joint face up, EX - exhaust face up [18].

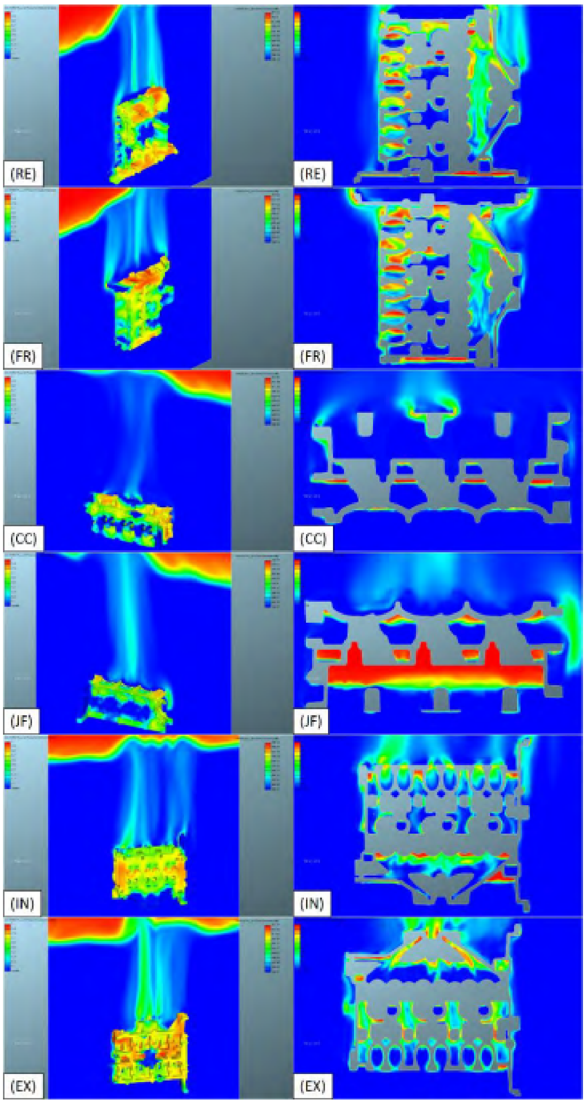


**Figure 2.31:** Vapor pattern and vapor entrapment inside cylinder heads after 20 seconds of quenching [18].

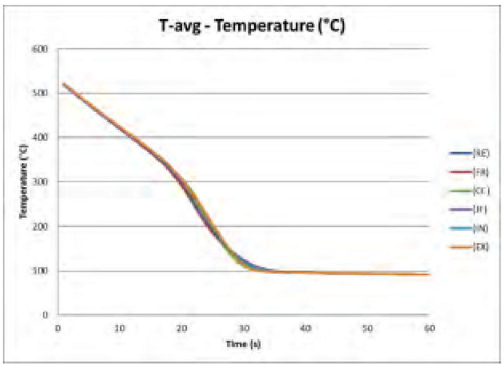


**Figure 2.32:** Cooling curves for all water quenching configurations [18].

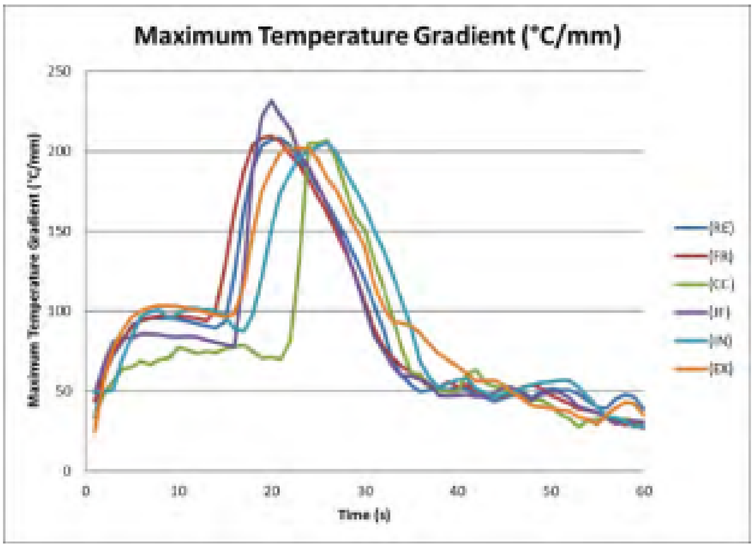


**Figure 2.33:** Maximum temperature gradients for all water quenching configurations [18].

### 2.5.7 Immersion Rate

Another factor that plays an important role in reducing distortion of quenched aluminium is the immersion rate [34]. In addition, two aspects that are often confused to be the same are the immersion rate and quench delay. However, immersion rate is the rate that the part enters the quenchants and this aspect is often disregarded. Quench delay refers to the time span between the end of heat treatment and the beginning of quenching. In a brief experiment [34] the effect of immersion rate was studied by having a quick and slow immersion rate inside 32% PAG polymer quenchant. In the first sample, the immersion rate was quick, and in the second sample, the immersion rate was slow with the same quench delay for both samples. The second sample with a slow immersion rate had severe distortion compared to the quickly immersed part, this can be seen in figure (2.34).

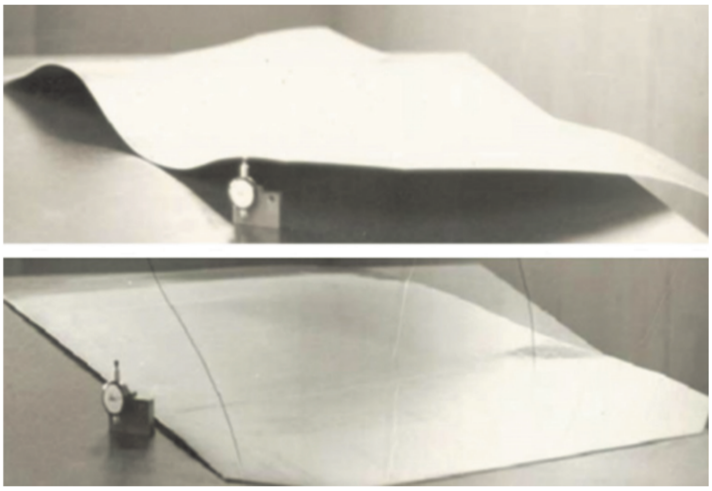

**Figure 2.34:** Sheets are 500×500 mm×1.0 mm thick immersed in PAG with two different immersion rates. On top, a sheet with slow immersion rate. On the bottom, a sheet with quick immersion [34].

# 3
# Method

This chapter covers the methodology used for conducting the thesis, with the main focus on HPDC and recent trends in this field. It presents the screening method of the literature study, data analytics, and simulation. Since the topic of Mega-Casting is still in the evolving stage - very few studies or research have been published and thus a pioneering approach was used in this study.

## 3.1 Methodological Framework

The selected design research methodology, DRM, is inspired by the DRM presented in [40]. It consists of 4 steps. The first step is about Research Clarifications which starts by understanding the background and problem area of the study. It's also about defining the aim and objective of the research. Furthermore, constructing and aligning the research questions with the aim of the study. This step also includes setting the main foundation of the research, such as defining the scope and delimitation of the research. These steps are accomplished through conducting a preliminary review of the literature.

The second step is the descriptive study. Since a preliminary or even comprehensive literature review doesn't provide the complete picture, a descriptive study is made to expand the understanding by collecting empirical data. The imperial data is qualitative data gathered from the expert interviews.

The third is the prescriptive step. It involves testing the findings from the literature review and the qualitative data gathered from interviews in order to further analyze the selected solution.

The fourth step is descriptive study, which includes analyzing and further testing the optimal solution. This falls outside of the scope of the study therefore a future recommendation was suggested.

## 3.2 Screening of Literature Study

In the literature review stage, a screening method was used to identify the relevant sources that matched the scope of the thesis. Moreover, to find the scientific sources, only scientific search engines and databases were utilized, such as Springer, ResearchGate, Elsevier (ScienceDirect), Chalmers Library as well as Google Scholar.

This ensured the credibility, reliability, and relevance of the findings.

The following steps were used, see figure (3.1):

1. **Select Specific Keywords**

   Since the topic is about geometrical variation in HPDC large castings, some keywords needed to be included in the search engines for the sake of relevance and filtration. Such keywords are:

   - geometrical variation
   - dimensional variation
   - distortions in HPDC components/parts,
   - Hyper-casting
   - Giga-press
   - plastic deformation
   - shrinkage
   - twisting
   - large casting

2. **Examine the *Abstract* and *Conclusions***

   After the first filtration step i.e. when finding a relevant headline/title of a source, the next step was not to analyze the whole source but to review the relevance through the abstract and the conclusions. If it was in the scope of the study and was related to distortions in HPDC castings, it was saved for the next step for detailed investigation and analysis.

3. **Examine the Whole Source**

   After the second step, the saved sources were analyzed, organized, and documented for later usage in the thesis. Furthermore, to verify the findings, some of the primary references were also analyzed to gain a deeper and comprehensive understanding but also validate the findings. Hence, a jump between steps- 2 and 3 was also a viable method applied.

4. **Organize and Combine**

   Lastly, to increase the clarity of the literature review, the articles were further organized into different subareas such as pre-quenching, quenching, and post-quenching. This was also done to easily detect any contrast between the findings.

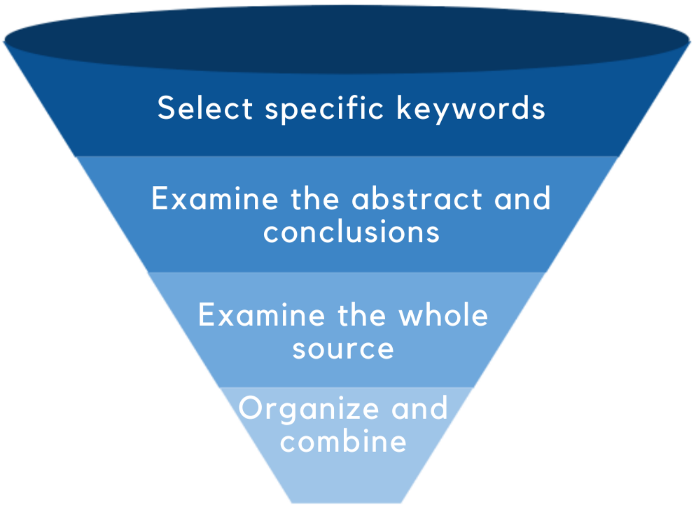


**Figure 3.1:** A funnel-like method for literature study.

## 3.3 Qualitative Study

Since mega-casting is a new topic, a large emphasis was placed on finding relevant experts with extensive years of experience in the field of HPDC. In addition, efforts were made to find interviewees outside the organization to expand the current knowledge. By conducting interviews with technical experts and academic researchers, the casting manager, in the qualitative phase of the thesis obtained several perspectives and insights. The interview questions were formulated based on the whole process chain of HPDC to ensure a thorough analysis, gather detailed insights, and easily find contractions between interviewees. Furthermore, the interviews were transcribed and analyzed by using the Affinity Mapping approach meaning that insights from each interviewee about a specific area were written on a post-it note and transferred to the specific area of HPDC.

The interview questions were semi-structured, meaning that the same predefined questions were asked for all interviewees but with some level of flexibility. The semi-structured allowed for organizing the answers in easier way and enabled, in-depth questions such as follow-up questions. In addition, the questions had small adjustments for the material expert and residual stress PhD student to ensure relevance. However, the questions were the same and followed the whole process chain of HPDC.

LinkedIn was the main platform to find the interviewees but some were recommended by the supervisor and interviewees themselves. Meaning, at the end of every interview, the interviewees were asked if they could recommend other experts. Most of the interviews were conducted digitally but some were conducted in person. Almost all interviews lasted around 1 hour.

## 3.4 Simulation

The findings from the literature study, and interview phase, will be further analyzed and verified in a casting simulation software. For this, a smaller part was designed to compensate for the long simulation time and the limited time frame of this project. Important to note that this is out of the scope of this project. The designed component had the essential attributes found in a large and complex mega-casting.

## 3.5 Quantitative Study

In order to verify some of the findings in the literature study and the interview insights, a quantitative study was also conducted. The quantitative part of the thesis is based on measurements and 3D scans of the mega-casting and some manual/rough measurement data. The data were provided by the factory engineers and the supervisor. A small data analysis regarding the production data of the Volvo mega-casting was carried out to extract valuable insights regarding the geometrical accuracy of the mega-casting. The data were cleaned, due to missing values, and plotted with Excel and MATLAB.

### 3.5.1 Tests in Foundry

Two sets of tests were conducted by the foundry engineers and the supervisor. The first set of tests was conducted under normal conditions. Most of the parameters were the same. However, the second set was conducted mainly to examine the effects of fast quenching (low quenching time) and exclude some parts of the mega-casting from quenching. A more comprehensive description of set 2:

- Test 1: Quenched with a very long quenching time and without changing the original quenching orientation
- Test 2: Very short quenching time and without dipping some areas
- Test 3: Different quenching sequence and without quenching some areas
- Test 4: Same as test 3, to elaborate, same quenching sequence and with the same areas not being quenched as test 3 but with increased die temperature (+30 Celcius)
- Test 5: Same as test 4 but with more areas not being quenched
- Test 6: Same as test 4 but with increased time for solidification inside the die (+30)
- Test 7: Same as test 4 but with increased water tank temperature and medium quenching time

## 3.6 Ethical Aspect

To protect privacy and confidentiality the interviewees were asked if they consent to have their names published. The method used to protect their privacy was coding for anonymity, by assigning a label to each interviewee e.g., E1, Expert 1. Moreover, adding their job titles provided context without compromising confidentiality. In addition, due to the confidentiality agreement with the company, all sensitive information and data will be hidden from the public. Numbers, figures, scales, and sensitive information will remain undisclosed.

# 4

# Results

This chapter contains the project results and a summary of the interview phase. Important to note that the results were based on the real mega-casting, however, the mega-casting pictures show a prototype.

## 4.1 Simulation

Performing simulations was outside the thesis scope, however, an attempt to verify the qualitative findings on simulation software was made. Due to unknown parameters and the complexity of the software, the simulations turned out to be very time-consuming. Despite these obstacles, a CAD model was designed and could be used in future research to validate the findings through simulation runs.

## 4.2 Data Analysis

For the first set of tests that were conducted in the foundry, multiple mega-castings were produced in the Volvo factory to be scanned and measured for geometrical variations. Figure 4.1 shows the geometrical variation of different points (total of 48 points) that have been scanned on the actual mega-casting. The middle line shows the nominal measurement and the critical points can be detected through the plot. The crucial points, marked in red, are - p13, p14, p17, p18, p21, p27, p28, p37, p38, and p48.

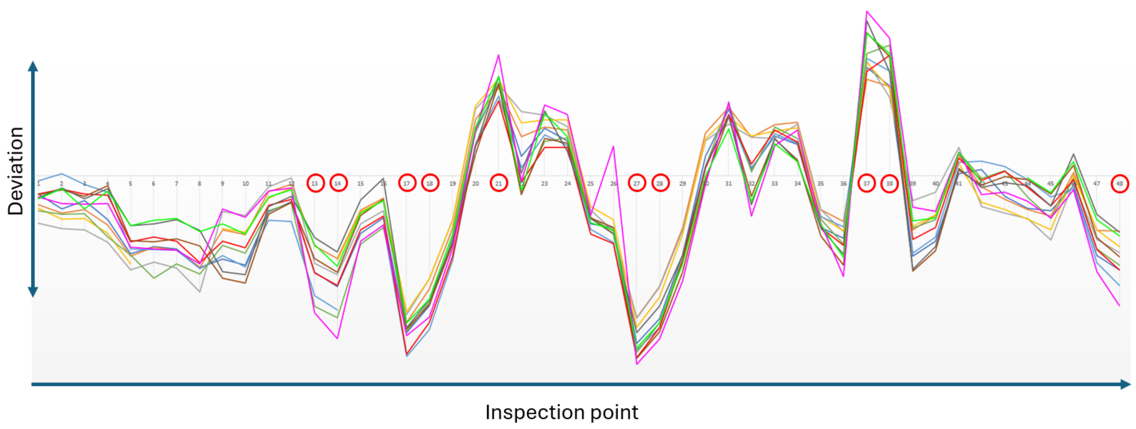


**Figure 4.1:** Inspected points on the mega-casting.

These critical points are located on the front legs and the upper part of the wheelhouse, see Figure 4.2. The scanning results also showed that the bending of the front legs is inwards and the wheelhouse outwards as shown in the same figure with red arrows.

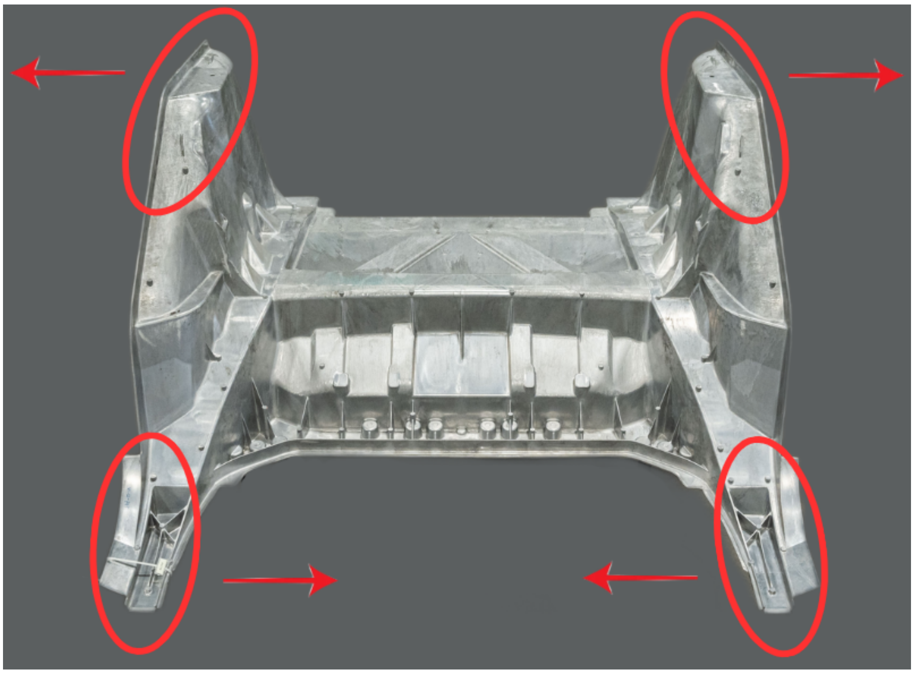

**Figure 4.2:** Red ellipses marking the sensitive areas and red arrows the bending behavior. Picture adapted from [41].

Some graphs from figure 4.1 were filtered for analyzing the vacuum effect on the variations of the points. The red graphs in figure 4.3 represent casting runs with no vacuum and in the blue ones, the vacuum was activated.

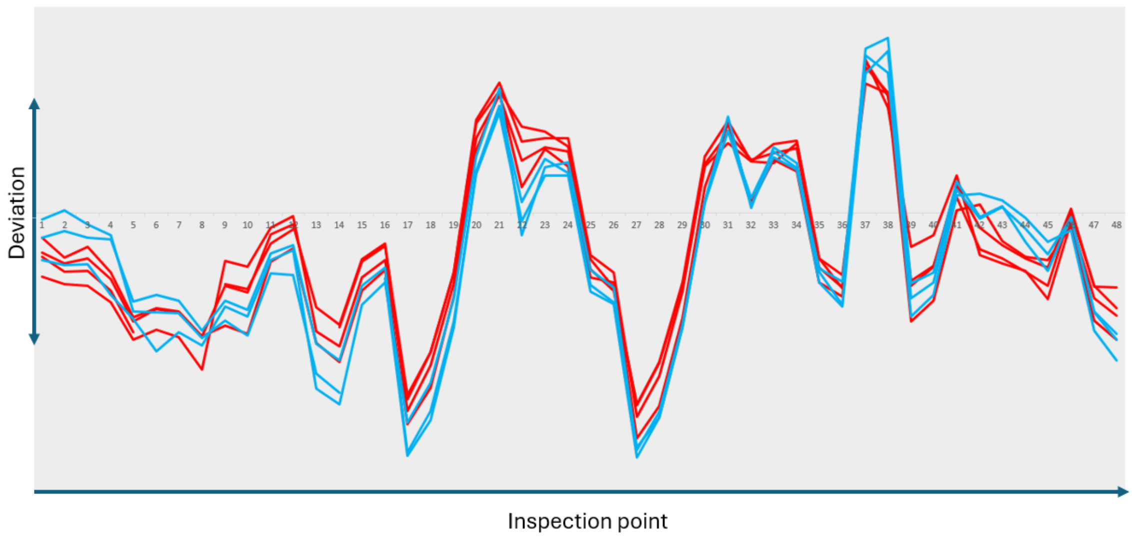


**Figure 4.3:** 4 Red graphs represent no vacuum-assisted casting runs while 3 blue graphs had vacuum assist.

Figure 4.3 shows that the vacuum-assisted runs are producing more variations in the critical points of the mega-casting (e.g. p18, p27, p28, p37, and p38). However, apprehending this observation regarding the runs of the mega-casting, a conclusion cannot be drawn. This is because other more significant parameters are unknown, such as the die temperature and cooling time inside the mold cavity. Furthermore, for robust analysis, the cycle runs are crucial because the runs with no vacuum assistance were conducted in later stages, and thus tool conditions were unknown.

Since the front legs appeared to be a sensitive area, the distance between the legs was measured in two places – *distance 1* and *distance 2*, see figure 4.4. A plot was generated to show the distance variation between the front legs. Figure 4.5 shows that tests 6 and 7 had the closest value to the nominal distances 1 & 2.

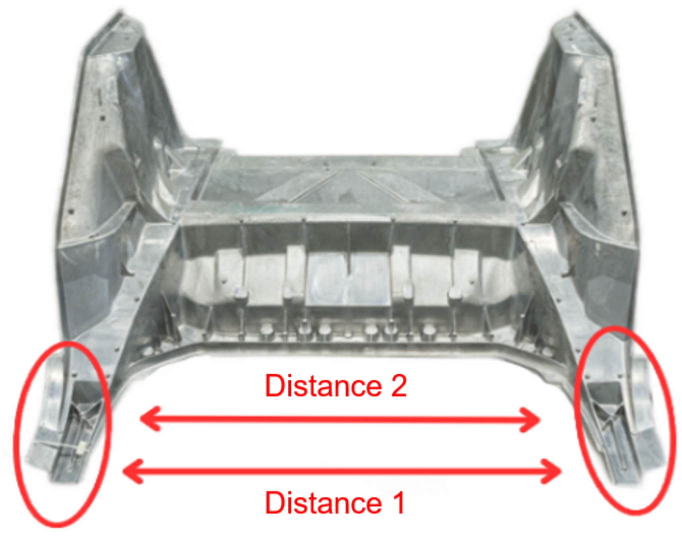


**Figure 4.4:** Distance measurement between the front legs. Picture adapted from [41].

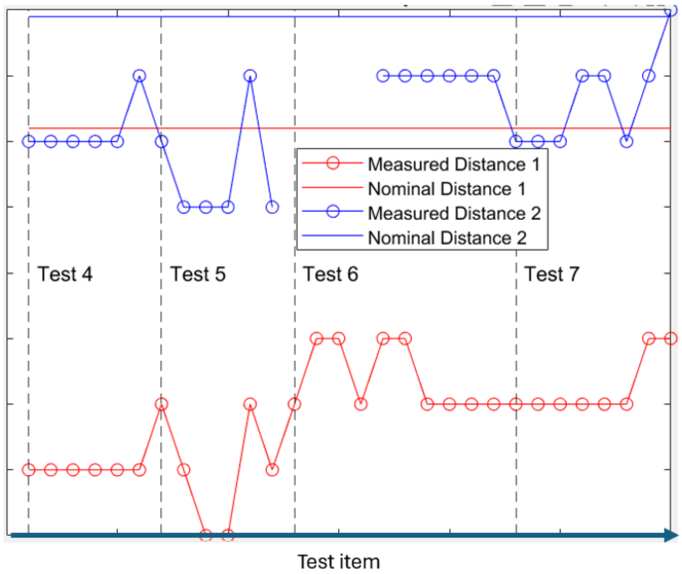


**Figure 4.5:** Different tests and their effect on distance 1 and 2.

The effect of the water temperature on the distortion was analyzed in figure 4.6 where each circle represents a measured instance. The x-axis of the plot represents the water temperature and the y-axis is the distance between the legs. The plot shows that the water temperature has an impact on the distortion. In addition, as the water temperature increased, the distances started to converge near the nominal distances, presented by the blue and red straight lines. Distance 2 had better results compared to distance 1, and it can be seen that distance 2 reached the nominal distance in the highest water temperature measured (in the top right corner). However, increasing the water temperature and reducing the cooling rate led to another problem during the trimming process. Since the part was hotter after being quenched, it got stuck to the trim-press.

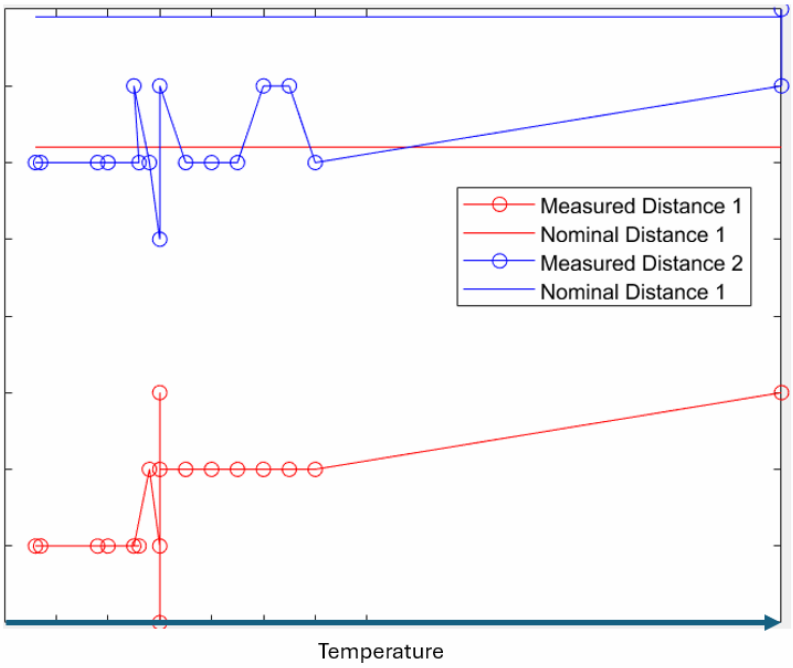


**Figure 4.6:** Quench temperatures and its effect on the measured distance 1 and 2.

Another test of the quench tank's temperature was conducted to see the effect of colder water on the distortion, see figure 4.7. The X-axis represents the temperature drop of the quench tank. The plot shows that, as the water cools, the more the distances diverge from their nominal value. The plot also showed a stabilization after a certain level of temperature.

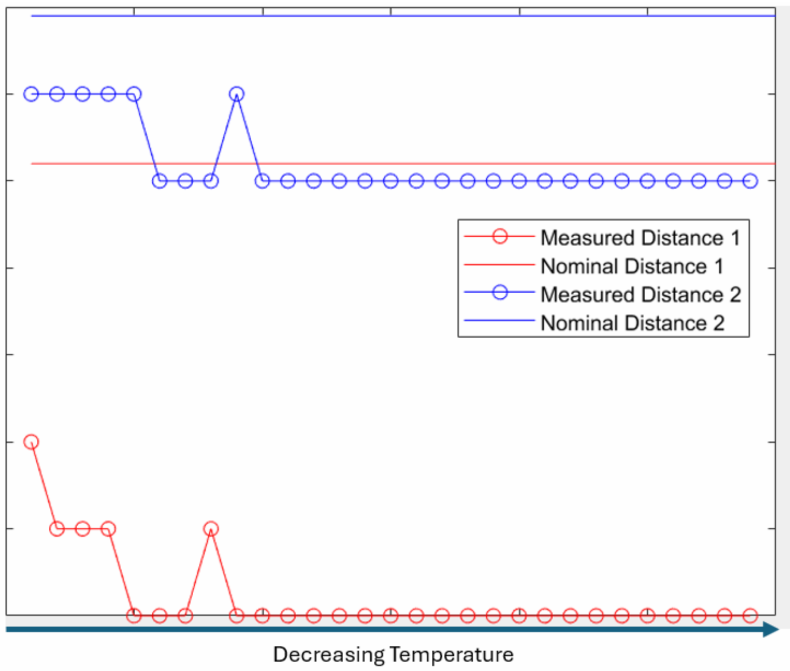


**Figure 4.7:** Cooling effect of quench tank on distance 1 and 2.

## 4.3 Summary of Experts Insights

A total of 10 interviews were conducted with knowledgeable people in the field of HPDC and die-casting. Additional 2 interviews were also conducted with a Ph.D. Student and a Materials experts to expand the knowledge of residual stresses. The interviewees are referred to as E(Number) (E for Expert) and their current work is also mentioned below.

- E1: Casting expert and CEO of a consulting business in HPDC
- E2: Ph.D, Assistant Professor Materials and Manufacturing - Casting
- E3: Professor in materials and manufacturing - casting
- E4: Associate Professor in Materials and Manufacturing - Casting
- E5: Site and Sales Manager of a casting company that focuses on die castings
- E6: Researcher in the field of HPDC
- E7: Technical Specialist casting
- E8: Casting expert and CEO of a casting company
- E9: Technical casting expert
- E10: Die Casting Tool Engineer
- E11: Ph.D student in residual stresses
- E12: Materials Expert

### 4.3.1 Gating System

All the interviewees agree that the gating system of mega-casting is a very important factor to consider when analyzing distortions. However, they highlighted different aspects of their claims.

According to E1, the gating system is typically way thicker than the actual casting, and thus a proper design is important to minimize the geometrical variation, especially when undergoing quenching.

E2, E3, E4, and E8, do agree with E1 and claim that a well-designed gating system is crucial for the:

- Flowability of the melt into the mold
- The temperature loss of the melt when injected
- Accuracy of the mega-casting
- Turbulence avoidance

E9 stated that the gating is a massive mass that is needed to make the mega-casting, and since it doesn't become the part, its weight should be minimized. However, both E9 and E4 explained that a good flow of the injected melt should be an even flow and for such large structural automotive parts, the gating system may be thicker than intended. The aspect of flowability was also discussed by E5, which explained that the main purpose of the gating system is to transfer the melt in a good way and thus, the turbulence should be reduced to achieve high-quality castings. E4 also highlighted the turbulence issue which means that it's an inevitable problem that will cause the inducements of small oxides in the melt. This also means that the gating design will affect how these oxides will emerge in the melt and could cause casting defects. E5 claims that, for larger castings, this issue could affect the bending behavior after the casting has solidified.

E3 stated that the wider the gating system is, the wavier the flow will be, which also means more defects. The professor (E3) continued by explaining two different gating designs and their differences:

- Fingers-like gating (similar to Xiaomi): made for a less wavy fill front, but fusion lines will occur.
- Fan-like gate (similar to the Tesla): Fusion line issue could be controlled, but a wavy fill front would occur.

However, he also suggested that, for the finger design, the fusion line issue could be controlled through proper pressure distribution in certain places. E3 means that the placement of the fingers could be optimized to restrict the twisting of the part.

Another important factor that was discussed by E3, E4 and E9 is the thickness of the gating. Since the gating also undergoes the solidification process, it will contain a lot of heat and thus will affect the temperature distribution of the mega-casting. For this reason, some of the experts mean that minimizing the weight of the gating system could benefit the accuracy of the mega-casting since the whole casting part would have a similar solidification rate. This phenomenon would result in less tendency or less total energy to cause warping of the casting, means E3. However, for better flowability of the melt, the thickness of the gating might be larger.

E2 and E3 claims that the geometrical accuracy of a large casting could be influenced by the flow of the melt and thus understanding the behavior of the bending effect in the nearby areas of the part is also important.

### 4.3.2 Shot Sleeve

The experts don't directly mention any connection between the shot sleeve velocity and the geometrical accuracy of the casting, instead, they claim that it's a matter of the locations of the air entrapments in the casting. E8 claims that the shot sleeve velocity needs to be "good enough" to prevent too much splashing into the mold.

Otherwise, without exception, all experts agreed that the shot sleeve velocity (second phase) has minimum effect on the geometrical variations or any type of distortion compared to the other parameters, such as the die temperature.

### 4.3.3 Die Design

Important to note that the die design also refers to the placement of the cooling channels.

One important point that E1 mentioned is the importance of draft angles. Since the part shrinks and sticks to the die, the ejection forces may be increased to be able to eject the part, which could result in deformations. To prevent this phenomenon, the design could be changed and draft angles could be introduced.

Another innovative way that was discussed by E1 and E10 is to design the part inaccurately, and later compensate for the distortions through the solidification and quenching phase. However, E10 means that this concept is very limited to certain designs and that the manufacturer should be very certain of the distortion behavior from the nominal shape. This approach is known as design for manufacturing or could be coined “design for distortion.”

According to E1, E2, and E8, in the future, 3D printing could be used to optimize the design of cooling channels. E1 also mentioned jet cooling and explained that this method can be timed and easily programmed (active control). He also claims that jet cooling facilitates the cooling of different wall thicknesses equally. However, the most important aspect is to have a continuous solidification that goes back into the shot sleeve. E2s hypothesis is that a die cannot have "the best" cooling system that compensates for different wall thicknesses. However, he believes that 3D printing may make it possible.

E8 also claims that die design is very important since it’s mainly about solidification and cooling. He highlighted that the different solidification rates would cause tensions in the casting. In addition, the hot spots area would have more sticking to the die and result in larger tension when ejected.

### 4.3.4 Die Temperature

E1 claims that it’s desirable to have uneven temperature distribution for HPDC castings, especially mega-casting. The expert reasons that the temperature at the end of the mold should be hotter than the gating area because the molten metal solidifies before reaching the end. However, E1 also states that when the mold is filled an even temperature is preferred. E2 agreed that preheating the end part of the mold would be beneficial but would be complex to implement. E8 also highlighted the problem of melt starting to solidify before fully filling the mold. The expert also mentioned that such a problem could cause cracks. However, E1 also stated that when the mold is filled, an even temperature of the die is preferred.

**Thermal History of the Die**

E1 mentioned that the type of spraying, conventional spray or micro spraying combined with how cold the die is, will have a major impact on the lifetime of the tool because the temperature difference between the liquid metal and the surface of the dies determines the fatigue load. In addition, having a cooler tool means quadrupling the fatigue load. Therefore having a hot tool is beneficial for the casting, E1 means.

### 4.3.5 Melt Temperature

According to E1, the melt temperature affects the mechanical properties and the cold shuts more than it affects the geometrical accuracy. He also highlighted that the sticking of the overflows and the gating system to the fixed die could cause geometrical variation.

According to E8, even if the filling time is in milliseconds (∼500 milliseconds), the melt temperature will change and start to solidify. On one hand, he points out that having a high temperature means a larger solidification range, thereby creating a hot and cool metal with a larger temperature difference in the same tool, leading to more tension. E5 also stated that the melt temperature does affect the shrinkage and a higher melt temperature means a higher risk for distortion of the part. On the other hand, E8 explains that too low temperature would cause the melt to solidify during injection, leading to difficulties in reaching the thinner parts far away from the gating system. Therefore the temperature of the metal is critical and thereby the properties of the metal according to E8. E4 claimed that, depending on the part design and cooling rates, the melt temperature could increase/decrease the distortion effects. Moreover, he mentioned that It's a complex combination of the parameters to optimize the casting and its quality.

### 4.3.6 Alloy Composition

E1 claimed that pure aluminium has a shrinkage rate of approximately 6.6% and adding silicon to the alloy composition would benefit the casting since silicon expands during solidification, leading to compensation for the shrinkage. E2 and E4 agreed with E1 and claimed that silicon in the alloy would be useful since it also improves the fluidity of the melt during the injection and thus improves the castability. E7 also mentioned that silicon is important for improving fluidity. E8 also noted the improvement of the fluidity and added that silicon content affects the melting temperature.

However, E4 stated that silicon generates more heat during the solidification process and the transformation phase could affect the geometrical accuracy of the casting. A significant amount of heat is also generated when different areas of the mega-casting solidify at different rates. This heat can cause the already-solidified areas to warm up again. He also highlighted that adding silicon to the alloy composition can enhance the strength of the casting. E9 claims that “from a theoretical point of view", silicon could affect the final dimensions of the mega-casting, but the impact wouldn't be huge.

Regardless, E4 highlighted that it cannot be concluded that residual stresses increase due to the higher temperature associated with the silicon content, and cause distortions. Instead, E4 claims that the distortion phenomenon is related to the cooling rates and the geometrical variations of the different sections in the casting. Nevertheless, E4 also noted that if the geometry is "well designed" to mitigate the stresses, then it's still "good to go" even with high silicon content. Consequently, a greater amount of heat needs to be managed and extracted from the mold.

### 4.3.7 Vacuum Assistance

E2 stated that HPDC with vacuum assistance reduces the air inside the mold before the filling process, contributing to fewer defects in the material. E4 noted that vacuum assistance makes it easier to fill the cavity and is also good for avoiding trapped air. E8 pointed out that vacuum is important because it affects the porosity and indirectly the geometrical variations. In addition, according to E3, the vacuum assistance affects the cooling conditions of the die and does not have a big impact on the final geometry of the casting. E9 agreed with E3 and claimed that vacuum has minimum impact on the casting in terms of geometrical variations.

### 4.3.8 Intensification Pressure

The effect of intensification pressure depends on the size and shape of the part according to E2, E3, E4, and E5. However, E9 claims that the intensification pressure does not have a big impact on the geometrical accuracy of the casting. Areas far away from the ingate, in a complex mega casted part, might not have the effect of the intensification pressure like areas close to the ingate according to E2. In other words, E2, believes that it wouldn't affect the whole component, only areas close to the ingate. E1 highlighted that intensification pressure is very important to compensate for the shrinkage porosity during the solidification and prevent degradation of mechanical properties. In addition, E1 explained that during solidification, the molten metal starts to form dendritic shapes, and if there are a lot of dendrites, a microporosity would emerge and impact the properties. Therefore the setup should be correct from the beginning according to E1.

E3, E4, and E5 means that the intensification pressure could be a contributing factor if the part design allows it. They claimed that, when having a design that has a thick gating system and then a thin area and then a thicker area again, if the thin part solidifies, the intensification pressure will not reach the second thicker area. Thus, this factor could affect the geometry if the part design allows it. See Figure 4.8

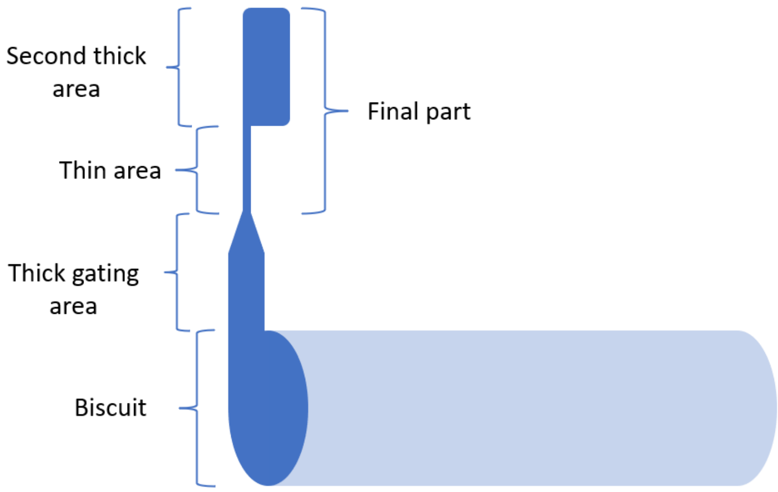


**Figure 4.8:** Simple representation of what E3, E4, and E5 means.

### 4.3.9 Cooling Time Inside The Cavity

According to E8, ejecting the part too early when it's warm will result in bending. In addition, waiting too long to take out the part will result in difficulty in ejecting the part due to shrinkage onto the die surface. E5 and E7 made a similar claim, that cooling time inside the cavity could cause some geometrical variations. According to E5, thin parts solidify faster than the biscuit and consequently, a longer waiting time for the biscuit to solidify is required. E9 also highlighted that the cooling time inside the mold is an important factor because by decreasing the cooling time from e.g. 20 to 10 seconds, the part would be semi-solid, and it may be possible to eject the part but problems will arise. However, increasing the cooling time from 20 to 40 seconds wouldn't affect the geometrical accuracy, but it would reduce productivity. According to E4, when cooling down from e.g. 700 to 200 degrees, more shrinkage has to be dealt with, however, it's more about the temperature difference and the cooling rates rather than the time the part spends in the cavity.

### 4.3.10 Ejection

E1 stated that the gripping area/point and timing of gripping have a massive impact on geometry. In addition, the lubrication is a crucial factor due to two reasons. Firstly, to have a good demolding (extraction), and secondly, to have a barrier between the die surface and the casting.

E5 and E7 stated that the ejection forces could affect the geometrical accuracy. E7 noted that waiting too long to eject the part is problematic because the part shrinks onto the die. Moreover, E5 stated that it is more important to focus on the mold ejection pins (including their quantity) and type of lubrication, rather than focusing on the selection of robot pins (which pick up the part after ejection).

According to E2, the number of ejection pins and their location should be designed to minimize the ejection forces during the ejection phase. E3 emphasized the ejection forces will affect the geometrical accuracy, ideally, the bending will be at the gate, but it could lead to twisting of the part.

E4 noted that having the ejection point on a weak area of the megacasted part could affect the final shape. E4 also mentioned that conducting a DOE in simulation software could minimize distortion by identifying the optimal positioning of the ejection pins. Another important aspect mentioned by E4 was that the MRA has a larger impact on the die rather than on the part distortion because the stresses are already built into the part.

E9 highlighted the importance of having an even distribution of ejection forces. He explained that areas shrinking into the die require higher force compared to those shrinking away, which need less force. Therefore, optimizing the placement of pins to reduce distortions is necessary.

E9 also mentioned that the gripping method matters. He noted that normally robots grip around the biscuit because it's a simple way to do it. However, other types of gripping could be needed instead of the simple "cylinder-gripping method", dependent on the part design. As an example, long and thin castings should have another type of gripping method because when the robot swings around, that could cause the part to distort.

According to E9, if the spraying of the lubricant (MRA) on the die surface is properly done, it would have very little effect on the part shape. However, if it's not done properly and not monitored, it could cause distortions due to the soldering problem (the sticking effect). When asked if more lubrication should be applied to areas that might stick to the die, E9 responded that it is better to apply the same amount all over the die surface to avoid over-application. Over-applying the MRA wouldn't be effective because it would get flushed off; instead, the focus should be on the type of MRA used, rather than the amount applied.

### 4.3.11 Quenching

According to E8, the dipping orientation and quenching media are important. Different quenchants have different cooling rates depending on the agent and temperature, but ultimately, achieving the best mechanical properties is essential. E8 explained that to achieve the desired properties, the quench delay (time from die to quench media) should be minimized. He also highlighted that if the media temperature is too low, larger tensions will develop within the part. The temperature difference is particularly important for products/parts with varying thicknesses; if the component has a uniform thickness, the tension would be smaller.

According to E1, to get a better understanding of the quenching phase, the manufacturer should try out different quenching orientations in combination with different immersion rates.

E3 emphasized that during the quenching, the part will bend around the biscuit and will be distorted after being taken out of the water bath. He also believes that leaving the part in the water bath a little longer may cause less warping. However, E3 means that the bending behavior is based on the part geometry and the temperature distribution before and after the quenching process. This means that the part temperature before quenching it will dictate the final shape. Furthermore, E3 claims that, in order to minimize the sensitivity of the part distortion, the manufacturer could keep the part a little longer in the mold. However, E3 means that even if the part has less tendency to warp, it would be sensitive after the trimming process because more internal stresses would be released. From a productivity point of view, E6 states that the manufacturers would eject the part directly after solidifying to optimize the cycle times.

Both E5 and E9 claimed that the quenching process (time in the bath and the dipping orientation) could affect the geometrical accuracy of the part. E5 means that dipping orientation could be optimized to minimize the warpage tendency through different dipping trials. E9 added that the immersion rate is also an important factor to consider because it could also influence the final shape. What E9 means is that a slower heat transfer during the quenching process could minimize the dimensional variations. If a certain type of quenchant could achieve this feature, it would be desirable according to E9.

E4 disagrees with E5 and E9, claiming that as long as the whole casting is dipped into the water, the orientation of the part doesn't affect the geometrical accuracy. However, E4 agrees on the point about the time inside the water bath. E4 means that the time the part spends in the water is important for monitoring the heat extraction level. For the same reason, E4 agrees with E9 that the type of quenchant affects the cooling rates, thereby influencing the geometrical accuracy.

E4s' hypothesis is that the severity of the geometrical inaccuracy is dependent on the temperature difference between the part (before immersion) and the water. His hypothesis is that the greater the temperature difference is, the greater the distortion tendency.

E7s' claims regarding the topic of quenching complement E4s' hypothesis. E7 claimed that lower water temperature during the quenching will result in the exacerbation of the residual stresses in the casting, which correspondingly suggests that the temperature difference (between the part and the water) influences the geometrical accuracy.

### 4.3.12 Trimming

E2 claimed that when trimming some parts of the mega-casting, e.g. overflows and the gating system, the internal stresses will be released, but new stresses will not be created. E9 means that the geometrical accuracy would not be significantly affected, even if there are stresses that will be released when trimming off some parts. E9 means that the geometrical accuracy would be influenced if the part is trimmed before being quenched, i.e. when the mega-casting is still hot. However, E4 disagrees with E9 and means that the stress release would affect the geometrical accuracy of the final part. E4 reasoned that if e.g. the gating area is solid and prevents that part from distorting, then the removal of the gating could lead to the freedom of part deformation.

E1 claimed that trimming can be used in a positive way to correct the distorted part to the intended design. To elaborate, E1 meant that if the design of the press tool is innovative, it can bend the part into shape and compensate for the distortions that occurred during the cooling process.

### 4.3.13 Residual Stresses

According to E11, thermal stresses are induced during the solidification phase in the diecast process. These stresses could either be tensile or compressive, however, they're also called residual stresses. E12 means that the part will not undergo plastic deformation when still in the diecasting machine because it's fixed and locked from bending. However, during ejection, different cooling rates will be introduced due to the air surrounding and thus affect the stress behavior. The quenching process also affects the internal stresses because the thinner areas will be exposed to compression and thicker to tension. E12 claims that simulation runs would be useful because they would show the direction of the stresses and thus be able to predict the bending behavior in certain conditions.

E11 also claims that these thermal loads induce the residual stresses within the part, and means that during the solidification and quenching the geometrical accuracy of the mega-casting would be influenced.

Regarding the gating system, E12 believes that the design is very important. He reasoned that a more uniform gate system with a similar thickness to the surrounding geometry is beneficial because the temperature difference between the part and the gate would be less. He argued that when rapidly cooling a mega-casting with a uniform thickness would reduce the segregation. E11s' claims are similar to E12s because he also claimed that the complexity of the mega-castings' design is a crucial factor to consider when analyzing the residual stresses especially if the thickness is not uniform. E11 means that the distribution of the thermal load would be complex and thus there is a high probability that it'll influence the residual stresses. E12 also added that the location of the gating is also an essential factor because it determines the macroscopic changes in stresses, meaning the changes in stress distribution within a cast part.

Another important aspect that was discussed was the die design and the placement of the cooling channels. E12 means that if the die was designed with a focus on residual stresses, the cooling channels would be placed closer to thick areas to create balanced cooling of the part. However, he claims that what is ideal from a residual stress point of view, may not be ideal for the mechanical properties.

Similar to the other E1s claims, E12 also mentioned the benefits of having a higher die temperature. E12 also mentioned that the flowability would be improved and that there is a possibility of pre-solidification during the injection phase. However, E12 added that the increment of the die temperature reduces the thermal gradient between thin and thick areas, and therefore it's better from a residual stress point of view.

From a theoretical point of view, E11 claims that the orientation of dipping and the quenching time would affect the residual stresses. E12 also agrees with E11s' hypothesis and means that the quenching orientation determines how fast thin and thick areas are solidifying and that contributes to residual stresses.

When the quenching parameters were discussed with E12, the expert mentioned the following parameters that have a big impact on the internal stresses:

- Orientation of dipping
- Quenching time
- Immersion rate

## 4.4 Cause and Effect Diagram for Geometrical Variation

Based on the literature findings combined with the data from some production runs and the interview phase, the following cause-and-effect diagram is generated see figure 4.9:

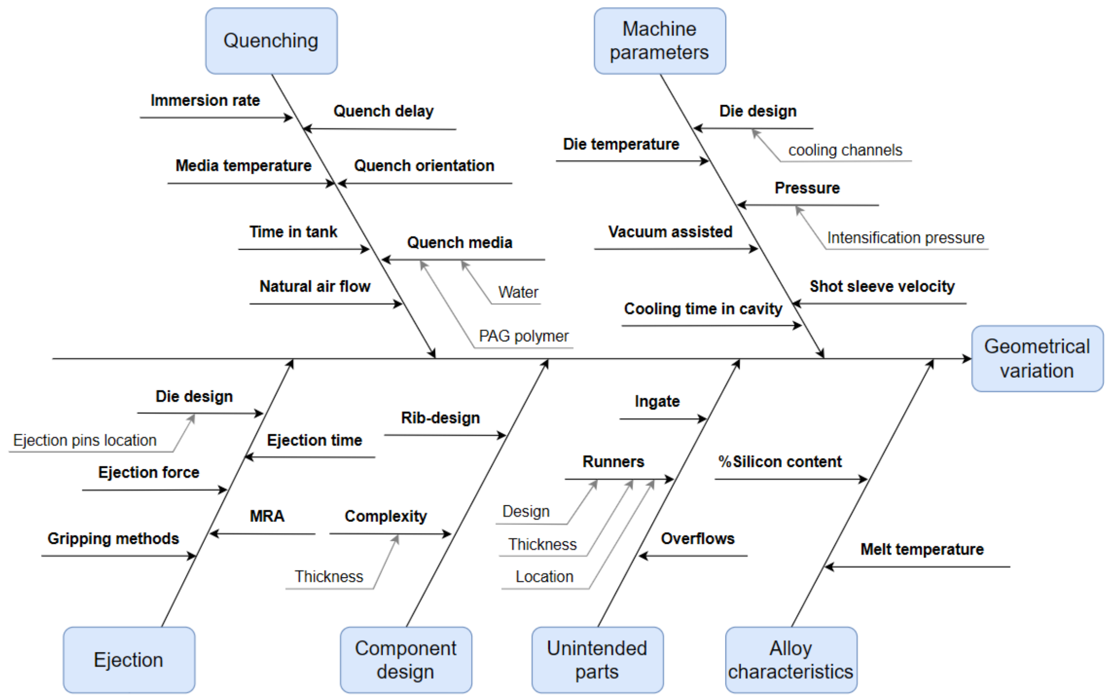


**Figure 4.9:** Final fishbone diagram for geometrical variation.

The fishbone has six main categories/causes of geometrical variation and provides the root causes. This diagram is mainly helpful when e.g. a geometry assurance engineer wants to map and analyze the phases/parameters that lead to geometrical variation. Two "bones" of the diagram, *Component design* and *Unintended parts* could be interpreted as one since their addition represents the whole mega-casting.

# 5 Discussion

Many car manufacturers have adopted the concept of mega-castings to produce single, large parts for major portions of the car structure. However, there remains a need for further extensive studies and tests to improve the quality and accuracy of such large castings.

As this thesis showed, there are many different contributors to geometrical variation for mega castings, such as the process parameters of the casting process and also the quenching and trimming phase. According to the experts/interviewees in combination with the literature findings, the root cause of all defects is the part design itself. The complexity, thickness differences, and the gating design seem to have a huge impact on the warping behavior. However, changing the part geometry and the gating design is not a simple approach since the whole die design would require changes (even the cooling channels) and that would be extremely costly. Thus, understanding the best combination between the process parameters as well as the quenching phase and the trimming would be essential.

Since the die temperature affects the cooling of the casting inside the mold cavity, it also affects the cooling rate and thus is an important factor. According to the literature findings, the combination of the die temperature and cooling time becomes important, especially for such large castings with different wall thicknesses. Therefore, optimizing these two parameters becomes essential because, according to the experts, it also affects the behavior of the casting when ejected from the die. Meaning that, extracting the casting while still hot could lead to plastic deformation due to lower yield strength, especially if the ejector pins are not optimized. Even the spraying of MRA is connected to these two parameters because it facilitates the extraction, else it could also contribute to geometrical variations because of the soldering problem. Based on the literature findings and the experts' response these parameters seem to have a significant impact if not set or applied properly. Applying lubrication before injecting the molten metal also affects the cooling rates since it balances the die temperature and thus influences the geometrical accuracy of the final shape.

Besides these parameters, the alloy composition is also an important factor to consider since the literature findings and the experts claim that silicon has multiple beneficial features in HPDC. Using silicon in aluminium alloys reduces the tendency for the soldering problem and thus decreases the chances of distorting the part. However, the experts noted that even though silicon improves the mechanical properties, it also affects the melt temperature and can generate more heat during the solidification phase. It was shown that residual stresses are induced during the phase transformation of the melt and also due to different cooling rates. Nevertheless, the correlation between the silicon content and distortion tendency is not very clear because although it expands (during solidification) and enhances the fluidity of the melt into the mold cavity, it also generates more heat which sends us back to the ejection and soldering problem. To understand the correlation between the distortion tendency and silicon content, a study needs to be conducted to study the side effects of the cooling rates.

Quenching is a critical step in HPDC and the literature findings have revealed that quenching has a direct impact on the mechanical properties and the residual stresses. Strength, hardness, and ductility are also affected. The level of the cooling rate is also of high importance because the higher the cooling rate the better the mechanical properties but that comes with an increase in residual stresses. Quenching a mega-casting could be considered as a rapid cooling method and thus the large casting will undergo a huge drop in temperature, a thermal shock. Therefore, the parameters that affect the cooling rate are of high importance. Furthermore, the quench technique also affects the cooling rate. For example, there is a difference between immersion quenching in water and spray quenching in water.

As it is illustrated in the fishbone diagram, the trimming phase is not included and that's because not enough research has been found regarding this topic. In addition, the interviewees had different opinions regarding this phase of the process chain.

An unexpected finding that was discussed with some of the interviewees was the ejection time which according to the experts could influence the final shape. Another interesting idea that was highlighted by one of the experts was the incorrect design of the mega-casting to compensate for the distortions in later stages.

The methodology used in this thesis project provided a better understanding of the whole HPDC process chain and aided in achieving the goal of the study which was deeper knowledge about HPDC and identification of the contributors. Starting the literature study provided an understanding of HPDC, interviewing experts filled the gaps in the research, and performing production tests validated some of the findings. The qualitative and quantitative methods used in this study increased the reliability of the findings.

The production data used for the quantitative study was secondary, meaning that there were uncertainties about the quality of the gathered data. This could impact the data's reliability and validity. However, the data was collected by experts. In addition, the insights from production data were consistent with the findings from the literature study and experts, indicating sufficient reliability.

## 5.1 Answering Research Questions

**Q1**: *What are the contributors to geometrical variation in mega-casted products/-parts?*

As discussed and shown in the fishbone diagram see figure 4.9, there are many contributors to geometrical variation. This includes machine parameters, such as placement and configuration of cooling channels, die temperature, cooling time in the cavity, and vacuum-assisted casting process. The machine parameters have an impact on the solidification pattern which in turn has an impact on stress distributions, shrinkage behavior, and repeatability of the process. But it also includes the quenching parameters, such as the media temperature, quench delay, type of quench media, and time in tank. This is because the part undergoes a large temperature drop, and experiences uneven cooling because of the non-uniform thickness. The type of media and its temperature also determines the cooling rate which in turn determines the distribution of residual stresses. Therefore all quenching factors combined determine the precision and consistency of the casting's dimensions.

Additional contributors are related to the ejection phase such as the location of ejection pins, and their forces. In addition, the amount of MRA applied and ejection time. These factors are related to soldering problems and shrinkage which could impede the extraction and result in distortion. Other contributors are related to component design and its complexity but also the unintended parts such as the gating, overflows, and their locations because they determine the contraction behavior. The alloy characteristics such as silicon content and melt temperature are also important because they influence the shrinkage and solidification process. See the fishbone figure 4.9 for all the contributors.

**Q2**: *What are the most crucial contributors?*

The design and complexity of the mega-casting are crucial to its sensitivity to geometrical deviation and variation. Therefore, the main root cause of geometrical variations is the design of the mega-casting itself. This refers to the gating design as well as the part design. The complexity and thickness of the mega-casting influence the temperature distribution throughout the whole process. In addition, the placement of the gating system is also of high importance since it's the hottest part of the mega-casting when ejected. The cooling rates, temperature distribution, and shrinkage behavior depend on the geometry of the mega-casting.

Many interviewees mentioned that the geometrical accuracy is much about the temperature difference throughout the process. That means that the quenching phase is also of high importance. Every interviewee was asked about the most crucial parameter in HPDC for such large castings, and the answer was almost the same, that it depends on the design of the mega-casting. Therefore finding the right and optimal combination between the parameters depends on the design. Meaning that what's considered optimal for a certain design may not be optimal for another design.

# 6

# Conclusion

The purpose of the thesis was to identify contributors to geometrical variation and improve the quality of mega-casted parts. This was accomplished after conducting a literature review, expert interview, and data analysis using qualitative and quantitative methods.

The key findings from this research showed that there are numerous contributors to geometrical variation. Furthermore, the significance of the contributors is mainly dependent on the part design. For that reason, the root cause of all geometrical variations is the design of the mega-casting. The design mainly includes the design of the mega-casting and the die design. To conclude, the location of the cooling channels and the thickness variation of the mega-casting will determine the temperature distribution as well as the solidification pattern. The gating design and its location determine the type of quality defects, solidification pattern, and distortion behavior because it pulls the part toward it as it solidifies.

Other findings include the effect of water temperature on distortion. As the water temperature increased the closer the measurements were to the nominal distances between the two legs indicating improved precision and reduced bending. This was due to the reduced cooling rate which highly influenced the residual stresses, mechanical properties, and distortion behavior. However, other problems appeared when increasing the water temperature such as sticking of the part onto the trim press.

# 7
# Future Recommendations

As discussed in the discussion chapter, changing the part design is not a simple solution. Another simpler solution for reducing the geometrical variability is through a DoE. Such a method could be utilized to understand the interactions between the input variables. Understanding the best combination between the process parameters as well as the quenching phase would be essential.

Finding the optimal combination of the identified contributors to produce accurate mega-castings with reduced geometrical variation is highly desirable. However, despite the benefits of finding the optimal combination, it would be very complex and time-consuming to consider all of them. Therefore a simpler DoE, considering the easily changeable and influential parameters was constructed, see figure 7.1. These parameters are mainly quench-related such as the quenching temperature, the orientation of dipping, water temperature, and also the cooling time in the mold cavity. These parameters were chosen mainly because the mega-casting undergoes a huge temperature drop.

Each of the mentioned parameters has two levels, meaning that a total of $2^4 = 16$ combinations. Furthermore, the DoE could be easily modified and changed e.g. another orientation trial could be added. However, increasing the number of input parameters would require more tests, and thus more resources will be used. For that reason, another recommendation is to conduct simulation tests on other parameters, such as the parameters of the ejection phase.

| Quenching Time | Water Temperature | Cooling Time in Cavity | Orientation |
|---|---|---|---|
| -1 | -1 | -1 | 1 |
| -1 | -1 | -1 | 2 |
| -1 | -1 | 1 | 1 |
| -1 | -1 | 1 | 2 |
| -1 | 1 | -1 | 1 |
| -1 | 1 | -1 | 2 |
| -1 | 1 | 1 | 1 |
| -1 | 1 | 1 | 2 |
| 1 | -1 | -1 | 1 |
| 1 | -1 | -1 | 2 |
| 1 | -1 | 1 | 1 |
| 1 | -1 | 1 | 2 |
| 1 | 1 | -1 | 1 |
| 1 | 1 | -1 | 2 |
| 1 | 1 | 1 | 1 |
| 1 | 1 | 1 | 2 |

**Figure 7.1:** A simple DoE with 16 trials.

# Bibliography


[1] V. C. S. AB, (Accessed on 01/25/2024), n.d. [Online]. Available: %7Bhttps://www.media.volvocars.com/se/sv-se/media/pressreleases/294589/photos%7D.

[2] K. Wärmefjord, J. Hansen, and R. Söderberg, "Challenges in geometry assurance of megacasting in the automotive industry", *Journal of Computing and Information Science in Engineering*, 2023.

[3] D. Carlisle, *Mega-casting trends for automotive manufacturers | ducker carlisle*, (Accessed on 01/25/2024), n.d. [Online]. Available: %7Bhttps://www.duckercarlisle.com/mega-casting-trends-for-automotive-manufacturers/%7D.

[4] R. Stumpf. "Why volvo will start 'mega-casting' its new electric vehicles". (2022), [Online]. Available: https://www.popsci.com/technology/volvo-to-start-mega-casting/. (accessed: 25.01.2024).

[5] K. Wärmefjord, R. Söderberg, A. Dagman, and L. Lindkvist, "Geometrical variation mode effect analysis (gvmea) for split lines", *Procedia CIRP*, vol. 92, pp. 94–99, 2020, 16th CIRP Conference on Computer Aided Tolerancing (CIRP CAT 2020), ISSN: 2212-8271. DOI: https://doi.org/10.1016/j.procir.2020.05.165. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2212827120309264.

[6] B. Schleich, K. Wärmefjord, R. Söderberg, and S. Wartzack, "Geometrical variations management 4.0: Towards next generation geometry assurance", *Procedia CIRP*, vol. 75, pp. 3–10, 2018, The 15th CIRP Conference on Computer Aided Tolerancing, CIRP CAT 2018, 11-13 June 2018, Milan, Italy, ISSN: 2212-8271. DOI: https://doi.org/10.1016/j.procir.2018.04.078. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2212827118305948.

[7] G. K. Sigworth and R. J. Donahue, "The metallurgy of aluminum alloys for structural high-pressure die castings", *International Journal of Metalcasting*, vol. 15, no. 3, pp. 1031–1046, 2021.

[8] F. Bonollo, N. Gramegna, and G. Timelli, "High-pressure die-casting: Contradictions and challenges", *JOM: the journal of the Minerals, Metals Materials Society*, 2015-05. DOI: 10.1007/s11837-015-1333-8.

[9] F. Casarotto, A. Franke, and R. Franke, "6 - high-pressure die-cast (hpdc) aluminium alloys for automotive applications", in *Advanced Materials in Automotive Engineering*, J. Rowe, Ed., Woodhead Publishing, 2012, pp. 109–149, ISBN: 978-1-84569-561-3. DOI: `https://doi.org/10.1533/9780857095466.109`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/B9781845695613500065`.

[10] M. Tiryakioḡlu and G. Totten, "Quenching aluminum components in water: Problems and alternatives", *ASM Proceedings: Heat Treating*, pp. 156–165, 1998-01.

[11] F. Peti, G. Lucian, S. Ioan, and C. Cristian, "Studies concerning the design of the runner, gate and venting systems in the case of the high pressure die casting technology", *ANNALS OF THE ORADEA UNIVERSITY. Fascicle of Management and Technological Engineering.*, vol. XIX (IX), 2010/2, 2010-09. DOI: `10.15660/AUOFMTE.2010-2.1926`.

[12] M. Iqbal, "Gating design criteria for sound casting", 2014. [Online]. Available: `https://api.semanticscholar.org/CorpusID:195176629`.

[13] M. E. Mehtedi, T. Mancia, P. Buonadonna, L. Guzzini, E. Santini, and A. Forcellese, "Design optimization of gate system on high pressure die casting of alsi13fe alloy by means of finite element simulations", *Procedia CIRP*, vol. 88, pp. 509–514, 2020, 13th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 17-19 July 2019, Gulf of Naples, Italy, ISSN: 2212-8271. DOI: `https://doi.org/10.1016/j.procir.2020.05.088`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S2212827120304108`.

[14] R. Svenningsson and H. Svensson, "Residual stresses in high pressure die castings", RISE, SWECAST, Tech. Rep. 2013-004, 2013, p. 39.

[15] "Residual stress analysis applied to hpdc aluminium components: A case study", *La metallurgia italiana : rivista mensile della Associazione fra gli industriali metallurgici italiani*, vol. 11-12, no. 113, 2021, ISSN: 0026-0843.

[16] P. Hofer, E. Kaschnitz, and P. Schumacher, "Distortion and residual stress in high-pressure die castings: Simulation and measurements", *JOM*, vol. 66, pp. 1638–1646, 2014-09. DOI: `10.1007/s11837-014-1118-5`.

[17] J. Campbell, "Chapter 10 - the 10 rules for good castings", in *Complete Casting Handbook (Second Edition)*, J. Campbell, Ed., Second Edition, Boston: Butterworth-Heinemann, 2015, pp. 535–638, ISBN: 978-0-444-63509-9. DOI: `https://doi.org/10.1016/B978-0-444-63509-9.00010-8`. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/B9780444635099000108`.

[18] *CFD Investigation of Quench Media and Orientation Effects on Structural Stress Induced in the Intense Quenching Processes for Aluminum Cylinder Heads*, vol. Heat Treat 2017: Proceedings from the 29th Heat Treating Society Conference and Exposition, Heat Treating Conference Proceedings, 2017-10, pp. 411–421. DOI: `10.31399/asm.cp.ht2017p0411`. eprint: `https://dl.`

asminternational.org/heat-treating/proceedings-pdf/HT2017/84130/411/669057/ht2017p0411.pdf. [Online]. Available: https://doi.org/10.31399/asm.cp.ht2017p0411.

[19] Y. Wang and C. Lee, "Design and optimization of conformal cooling channels for increasing cooling efficiency in injection molding", *Applied Sciences*, vol. 13, p. 7437, 2023-06. DOI: 10.3390/app13137437.

[20] T. Kim, K. Jin, N. Kim, and B. Kim, *Numerical analysis and optimal design to reduce residual stresses and deformations of die casting baseplate after ejection - journal of mechanical science and technology*, 2015-07. [Online]. Available: https://link.springer.com/article/10.1007/s12206-015-0625-9#citeas.

[21] H. Dini, N.-E. Andersson, and A. Jarfors, "Effect of process parameters on distortion and residual stress of high-pressure die-cast az91d components", *International Journal of Metalcasting*, vol. 12, 2017-11. DOI: 10.1007/s40962-017-0186-z.

[22] G. Campatelli and A. Scippa, "A heuristic approach to meet geometric tolerance in high pressure die casting", *Simulation Modelling Practice and Theory*, vol. 22, pp. 109–122, 2012, ISSN: 1569-190X. DOI: https://doi.org/10.1016/j.simpat.2011.11.003. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1569190X11001808.

[23] C. El, A. Bouayad, and M. Alami, "The effect of mold and pouring temperature on hardness and microstructure of a hpdc hyper- eutectic aluminum alloy", *International Journal of Engineering research and technology*, vol. Volume 4, pp 1162–1165, 2015-03.

[24] Z. Niu, G. Liu, T. Li, and S. Ji, "Effect of high pressure die casting on the castability, defects and mechanical properties of aluminium alloys in extra-large thin-wall castings", *Journal of Materials Processing Technology*, vol. 303, p. 117 525, 2022, ISSN: 0924-0136. DOI: https://doi.org/10.1016/j.jmatprotec.2022.117525. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0924013622000371.

[25] X. Dong, X. Zhu, and S. Ji, "Effect of super vacuum assisted high pressure die casting on the repeatability of mechanical properties of al-si-mg-mn die-cast alloys", *Journal of Materials Processing Technology*, vol. 266, pp. 105–113, 2019.

[26] O. Köser, J. Rückert, and P. Ubl, *Part ejection in magnesium high pressure die casting*, 2021.

[27] S. Ueda, S. Sannakanishi, H. Shiga, M. K. Faiz, and M. Yoshida, "Evaluation of ejection force for die castings by fem thermal stress analysis with elasto-plastic-creep model", *Materials Transactions*, vol. 63, no. 2, pp. 217–223, 2022.

[28] A. Monroe and P. Sanders, "The need for a new approach to soldering in high pressure die casting", *International Journal of Metalcasting*, vol. 15, no. 2, pp. 391–397, 2021.

[29] Z. Chen, “Formation and progression of die soldering during high pressure die casting”, *Materials Science and Engineering: A*, vol. 397, no. 1-2, pp. 356–369, 2005.

[30] M. M. Makhlouf and D. Apelian, “Casting characteristics of aluminum die casting alloys”, 2002-02. DOI: 10.2172/792701. [Online]. Available: https://www.osti.gov/biblio/792701.

[31] B. Zabala, C. Raone, A. Igartua, *et al.*, “Evaluation hpdc lubricant spraying for improved cooling and die protection”, 2016-06.

[32] D. Mehdi, “Effect of silicon content on the mechanical properties of aluminum alloy”, *International Research Journal of Engineering and Technology*, vol. 2, pp. 1326–1330, 2015-07.

[33] D. S. MacKenzie, “Quenching of aluminum alloys”, in *Aluminum Science and Technology*, K. Anderson, J. Weritz, and J. G. Kaufman, Eds., vol. 2A, ASM International, 2018, pp. 438–461. DOI: 10.31399/asm.hb.v02a.a0006506. [Online]. Available: https://dl.asminternational.org/handbooks/edited-volume/10/chapter/117748/Quenching-of-Aluminum-Alloys.

[34] S. MacKenzie, *HTM Journal of Heat Treatment and Materials*, vol. 75, no. 1, pp. 23–34, 2020. DOI: doi:10.3139/105.110401. [Online]. Available: https://doi.org/10.3139/105.110401.

[35] G. E. Totten, C. E. Bates, and N. Clinton, *Handbook of quenchants and quenching technology*. ASM international, 1993.

[36] H. Tensi and P. Stitzelberger-Jacob, “Effects of rewetting on the cooling of quenched aluminum specimens”, *HTM, Haerterei-Tech. Mitt*, vol. 43, no. 3, pp. 148–155, 1988.

[37] H. M. Tensi, P. Stitzelberger-Jakob, and G. E. Totten, “Surface rewetting of aluminum.”, *Advanced materials & processes*, vol. 156, no. 6, H15–H15, 1999.

[38] Y. Lei, H. Zhao, W. Bai, Q. Xu, and Z. Han, “Microstructure, mechanical properties and residual stress of high vacuum die casting alsi10mgmn alloys with different spray quenching”, *Journal of Materials Processing Technology*, vol. 325, p. 118 284, 2024, ISSN: 0924-0136. DOI: https://doi.org/10.1016/j.jmatprotec.2024.118284. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0924013624000025.

[39] R. D. Lopez-Garcia, I. Medina-Juárez, and A. Maldonado-Reyes, “Effect of quenching parameters on distortion phenomena in aisi 4340 steel”, *Metals*, vol. 12, no. 5, 2022, ISSN: 2075-4701. DOI: 10.3390/met12050759. [Online]. Available: https://www.mdpi.com/2075-4701/12/5/759.

[40] L. T. Blessing and A. Chakrabarti, *DRM: A design reseach methodology*. Springer, 2009.

[41] *Mega casting*, n.d. [Online]. Available: https://www.media.volvocars.com/global/en-gb/media/photos/327230/mega-casting-8.

**DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE**
**CHALMERS UNIVERSITY OF TECHNOLOGY**
Gothenburg, Sweden
www.chalmers.se

AVANCEZ
1829
CHALMERS
UNIVERSITY OF TECHNOLOGY