JÖNKÖPING UNIVERSITY
School of Engineering

Die life prediction using High Pressure Die Casting simulations

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Abstract

Global trends in automotive industry for weight reduction drives an interest for casting of structural aluminum parts. High pressure die casting (HPDC) is chosen for this purpose since it enables manufacturing of large series parts where complexity and repeatability is demanded. Aluminum alloys have hence been developed through the years to obtain suitable mechanical properties for high strength parts. These alloys have been investigated to predict the types of potential failure mechanisms during HPDC in order to determine die life through simulations. Die life prediction was performed through simulations in MAGMAsoft 5.4 with the help of a die life module, which is based on thermal stresses generated in the die material during casting cycles. Fatigue data at elevated temperature obtained from literature review of AISI H11 tool steel was complemented to the Wöhler curve in the software database.

Comparison of two aluminum alloys showed that chemical composition had a major influence on die life. Chemical composition had a direct impact on solidification time and with longer solidification time, the thermal load on the die increased. Since the stress range on the die is temperature dependent, the ability of heat transfer over time proved to be critical for die life results. The most crucial process parameter to achieve a longer die life was constant cooling by tempering channels, due to their high potential to remove heat. Tempering channels and die spray also prevent the die from exceeding a critical temperature resulting in soldering formation. Mold erosion was consistently observed in the same location for all simulations.

Sammanfattning

Globala trender inom fordonsindustrin att reducera vikt driver intresset framåt för gjutning av bärande aluminium gods. Pressgjutning som tillverkningsmetod väljs därför till detta ändamål eftersom det möjliggör tillverkning i stora serier där komplexitet och repeterbarhet efterfrågas. Aluminiumlegeringar har genom åren utvecklats för att erhålla lämpliga mekaniska egenskapen för delar med hög hållfasthet. Dessa legeringar har undersökts för att förutsäga vilka typer av potentiella felmekanismer med pressgjutning som kan uppstå för att bestämma livslängden genom simuleringar. För att förutsäga livslängden utfördes simuleringar i MAGMAsoft 5.4 med hjälp av en livslängdsmodul, som är baserad på termiska spänningar genererade i gjutformen under gjutningscyklerna. Utmattningsdata vid förhöjd temperatur erhölls under litteraturgranskning av AISI H11 verktygsstål samt kompletterades med Wöhler-kurvan i mjukvarudatabasen.

Jämförelse av två aluminiumlegeringar visade att den kemiska sammansättningen hade en stor inverkan på gjutformarnas livslängd. Den kemiska sammansättningen hade en direkt inverkan på stelningstiden, där en längre stelningstid ökade den termiska belastningen på gjutformen. Eftersom spänningsförhållandet är temperaturberoende visade sig värmeöverföring över tid vara kritisk för livslängdsresultaten. Den mest avgörande processparametern för att uppnå en lång livslängd var konstant kylning från kylkanaler på grund av deras förmåga att avlägsna värme. Kylkanaler och yt-spray förhindrade också att gjutformarna överskrider en kritisk temperatur för pålödning. Erosionsbildning visade sig vara konsekvent på samma område vid alla simuleringar.

Keywords

HPDC, structural HPDC, high pressure die casting, aluminum HPDC, MAGMA, thermal fatigue, stress simulation.

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1 Introduction

This thesis is simulation based where prediction of die life for aluminum high pressure die casting (HPDC) is studied. It is the final project work of the one year Foundry Master Program at Jönköping University. Performing a systematic investigation of failure mechanism in real production is an extremely complex and expensive task. While laboratory test methods are available where tool steel performance can be evaluated, these methods can be expensive, cumbersome and time consuming. Simulation tools could in this regard provide necessary insights before moving on to laboratory and industrial/semi-industrial tests. Hence, for the purpose of this thesis, MAGMAsoft is utilized to study the impact of aluminum alloy composition, casting temperature and process parameters on the die-aluminum interaction and consequently die life evaluation. Literature survey of two selected aluminum alloys was carried out in order to gather information to perform die life simulations in MAGMAsoft. Simulation results will be based on temperature where potential failure mechanism in the die material will be revealed based on thermal stresses. Focus in the simulations will be based on temperature and possible chemical reaction will be tackled in the theoretical background based on literature surveys.

1.1 Background

This work has been carried out at Jönköping University in collaboration with Uddeholms AB, which is a world leading tool steel company that produces tool steels within applications of hot work, cold work, plastic moulding and components. Within the hot work segment, tool steels for HPDC is one of the most important areas for Uddeholms AB. To keep its competitiveness, non-ferrous casting alloys needs to be investigated to predict which types of failure mechanisms might occur on the die material. These alloys also set a demand for next generation tool steels with properties that should be able to provide a suitable die life for the application.

HPDC is a widely used manufacturing process for large series production of lightweight components. The rapid process where molten metal is injected between two permanent molds with high velocity and solidifies under high pressure, results in a short cycle manufacturing process with high repeatability. The process provides castings with good tolerances and possibility to shape parts with thin wall thickness.

Historically aluminum HPDC parts have been used in applications that desire lightweight and low safety requirements with aspects of critical loads. Global trends in the fields of HPDC have shown a growth of lightweight parts, especially in the automotive segment due to weight reduction demands. These trends have led to cast aluminum parts, which require more complex die designs and bigger die dimensions since several parts from previous manufacturing processes have been integrated to one. In this regard, aluminum alloys for high strength parts have been developed through the years to receive castings with suitable mechanical properties as cast and through post process such as heat treatment. A problem with these alloys have been the level of iron content, which counteract die soldering formation as a consequence of yield strength due to the formation of brittle iron rich needles [1].

MAGMAsoft is a simulation software, which the foundry industry uses to simulate casting processes. The software is widely used for HPDC foundries to simulate the casting process of their dies before manufacturing in order to make a correct die design suitable for the process [2]. MAGMAsoft has launched a module in order to predict die life based on thermal stresses, module 5.4, which was applied in this thesis work.

Improvement in mechanical performance of the aluminum alloys is perceived to pose challenges in being able to maintain good die life in HPDC. A systematic evaluation of the impact of processing these structural alloys on the tool life prediction would enable proper selection of the currently available tool steel materials and could aid in the development of new tooling solutions.

This thesis according to discussion above is an attempt to explain potential failure mechanism on the die material based on HPDC manufacturing of structural parts made in aluminum. Both chemical and thermal reactions which could decrease die life needs to be tackled in order to get a good understanding of how these affects the die material.

1.2 Purpose and research questions

The purpose of this work is to investigate how structural aluminum HPDC affects the die life, based on failure mechanism through simulations. Gain a good understanding of the alloys and its influence on die life based on literature survey.

The work is divided into two main research questions with three sub-questions.

- What failure mechanisms determine the die life in HPDC?

- What is the influence on die life from processing variables such as:
    - How will casting cycle performed with no cooling resulting in superheat influence the die life?
    - What influence will time specified die spray have on the die life without internal cooling?
    - How will constant cooling from tempering channels influence the die life during the casting cycle?

1.3 Delimitations

In order to save computational time, the CAD models were made in a simplified and symmetric way. One benefit with HPDC is the design freedom and therefore many parts have a very complex design, but to obviate the thesis to become extensive this has been delimitated. Investigation of process parameters will be limited to minimize data volume for evaluation. No physical test or experiment was conducted during the work.

2 Theoretical background

2.1 High pressure die casting process

HPDC is a manufacturing process where molten metal is injected between two die cavities under high pressure. The process is very rapid and used for large series production of aluminum, magnesium, brass and zinc alloys. The benefit with HPDC is that large series production with net-shape, repeatability and tight tolerances can be achieved. The setup of the process is that two machined cavities, normally made in chromium martensitic tool steel such as AISI H13 or H11 are inserted into two holder blocks. The holder blocks are closed together with a high clamping force before the molten metal is poured from the chamber into the shot sleeve by a ladle.

A piston forces the molten metal from the shot sleeve to the gate and into the cavity with high velocity. Cooling or tempering channels are normally used in the machined cavities, which enhance a rapid solidification of the molten metal after injection. After solidification, the dies are opened and the cast part is ejected with help of ejector pins. Before the dies are closed for the next cycle, die spray is normally applied where the two cavities are sprayed with cooling media and lubrication [3]. Figure 1 shows a schematic view of how injection and solidification occurs in the process.

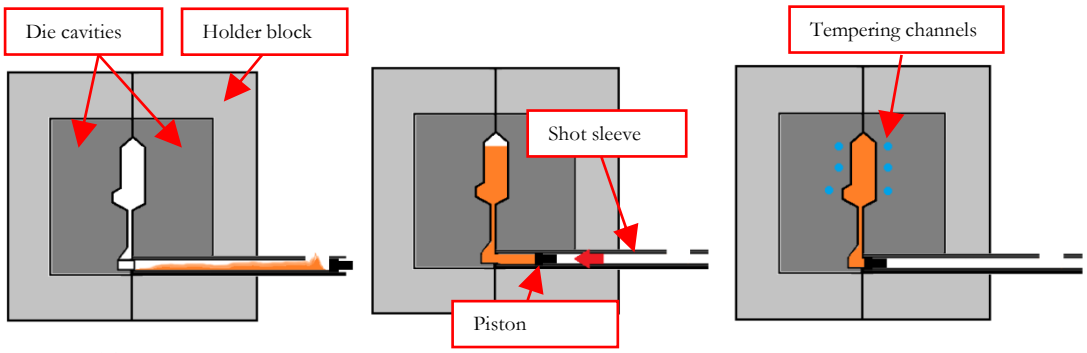

Figure 1. The casting sequence, starting with pouring in the shot sleeve followed by injection and solidification with help of tempering channels.

2.2 Structural aluminum HPDC

Automotive segment demands for lightweight components have increased in order to obtain low fuel consumption and less environmental impact. To fulfill these demands, lightweight parts manufactured through HPDC have been more common where ferrous materials would otherwise be used. These parts are different from traditional HPDC parts in the sense that they are normally large and have a complex design where several parts have been integrated to one. The wall thickness is normally 1-3 millimeters. However, perhaps the biggest difference is the chemical composition of the aluminum alloys, which allows an increase in mechanical properties. Traditional HPDC aluminum alloys have a low yield strength compared to ferrous materials and for that reason, the parts are normally used where impact toughness and yield strength are not a critical demand. Therefore traditional HPDC aluminum parts are used as engine blocks and gearboxes, which desires low weight and no safety requirements from loads. HPDC parts, which are applied as structural components are normally used in the car body. These parts desire high yield strength and suitable elongation in order to resist high mechanical load in a crash situation.

Figure 2 show a lightweight body frame part shaped by two die cavities in a HPDC process. Advantages of castings in comparison with steel in structural components are that the design freedom make it possible to have specific redirection of forces and allows a variation in wall thickness to encounter loads [1, 3].

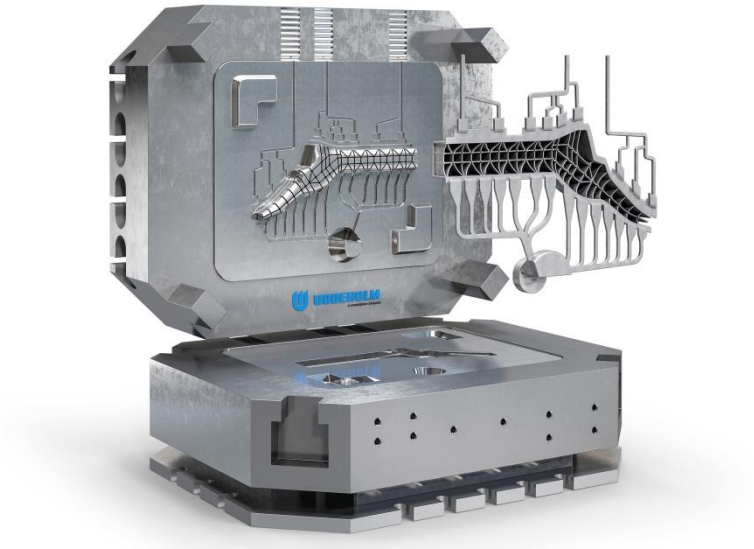

Figure 2. Visualization of structural HPDC part and die cavities for automotive segment.

The ability to use cast parts for high strength components includes post process, such as heat treatment, when applied can lead to an increase in the yield strength and still have a suitable elongation. Heat treatment of Al-HPDC parts commonly employed the T4, T5, T6 and T7 tempers [4]. However, heat treatment of HPDC components could promote surface defects, blistering formation occurs when already existing defects becomes surface defects. During filling, turbulent flow enhances mixture of air or lubrication with the molten metal, consequently entrapped gas porosity becomes compressed during solidification. When the casting is heated to elevated temperature, compressed gas pores expands due to the softening of surrounding material. When the gas pores reaches the surface, bubble shaped defects is exposed. In order to reduce the risk of blistering, the whole process chain needs to be controlled; alloy composition, melt treatment, degassing, filtering and die design. The amount of entrapped gases could also be reduced by applying a casting atmosphere below 50 mbar, this is known as high vacuum die casting. Figure 3 show the typical property range within the normal variation obtained in HPDC components that can be improved by the different heat treatments processes for an AlSi10MnMg alloy. For components where high yield strength is desired, T5 and T6 tempers are more suitable [5, 6].

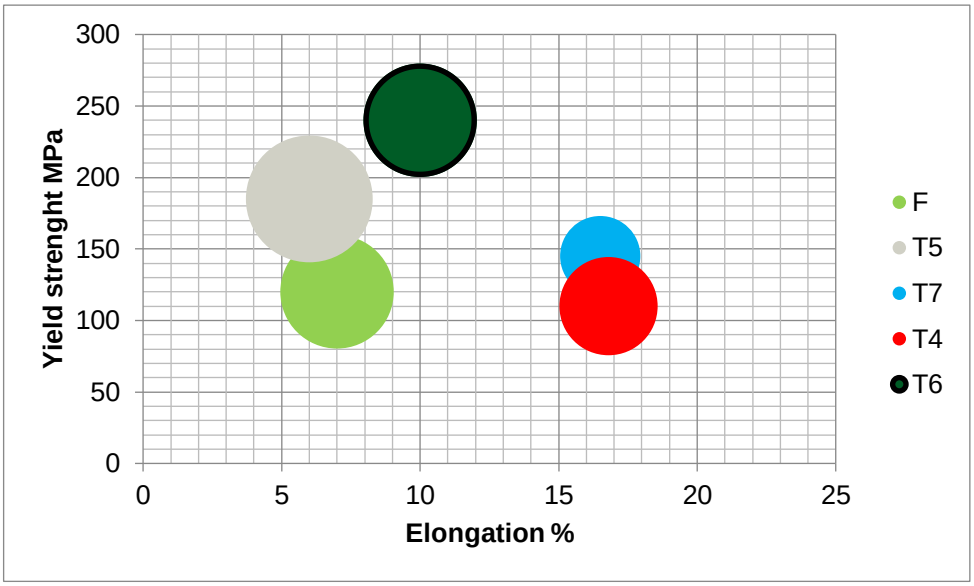

Figure 3. Range of properties received in F (as cast) and different heat treatment stages.

T5 temper is a heat treatment process where the casting is subjected directly to artificial aging without any high temperature solution treatment. The ageing process increases the strength while providing an acceptable elongation. The yield strength can be increased further by longer holding times at the ageing temperature, which could result in a decrease in elongation.

T6 temper is a full heat treatment process in three steps that further improves the mechanical properties of the casting. The first step is the solution heat treatment where the casting is heated to a high temperature for a specific time. During the solution heat treatment, all alloy elements in the aluminum alloy will be dissolved in a solid solution. The second step is quenching, the casting is now rapidly cooled from the high solution temperature, which prevents the alloy elements from formation of precipitates. The last step is the artificial aging, where the aging is performed in the same way as for the T5 temper. The casting is heated and held at an elevated temperature where the alloy element starts to form ordered arrays of atoms, which provides strength to the material [5].

2.3 Structural aluminum alloys

There are two major groups for structural aluminum alloys [3], the most common is the AlSiMg with silicon content between 6-12 %, magnesium content around 0.7 % and a low iron content under 0.2 %. The other group is the AlMgSi alloy with magnesium content between 4-6 %, silicon content under 3% and iron content around 0.2 %.

The AlSiMg alloy exhibits good mechanical properties after heat treatment and are easy to cast. AlMgSi alloy however provides good mechanical properties in the as cast condition without any heat treatment but is expected to be more aggressive towards the die during casting. According to Rheinfelden alloys, which manufactures the two alloys that can be seen in Table 1 and 2. The solidification range for Silafont-36 an AlSiMg alloy, is between 590-550 °C and for Magsimal-59 an AlMgSi alloy, between 618-580 °C. The die life prediction for Silafont-36 is similar to the standard AlSi10Mg (Fe) alloy and >90% for the Magsimal-59. Based on the data from Rheinfelden alloys guideline the pouring temperature for Silafont 36 are recommended to be between 680-710 °C and between 690-730 °C for Magsimal 59 [6]. Note that this is the temperature of the molten metal when is poured into

the shot sleeve and not the temperature it will have during surface contact with the cavity dies.

Table 1. Chemical analysis of a AlSiMg alloy, Silafont-36.

	Si	Fe	Cu	Mn	Mg	Zn	Ti	Sr	P
Min	9.5			0.5	0.1		0.04	0.010	
max	11.5	0.15	0.03	0.8	0.5	0.07	0.15	0.025	0.001

Table 2. Chemical analysis of a AlMgSi alloy, Magsimal-59.

	Si	Fe	Cu	Mn	Mg	Zn	Ti	Be
Min	1.8			0.5	5.0			
Max	2.6	0.2	0.03	0.8	6.0	0.07	0.20	0.004

Silicon (Si) is a common alloy element in aluminum alloys for HPDC since it improves castability in the form of resistance to hot tear, increase of fluidity and feeding capability. While, fluidity is a very important factor for the alloy to fill out the casting, the other important property of silicon is that it contributes to high heat of fusion or heat release and a corresponding change of temperature where the alloy freezes. Si together with iron can however have disadvantages on the casting due to the formation of brittle compound plates [7].

Based on the phase diagram, see Figure 4 the eutectic for Al-Si is at 12.6 wt. % of Si at 577 °C [8]. If the Si content is lower than 12.6 wt. % a hypoeutectic microstructure will be established due to the solidification path. The solidification will start with forming α-Al dendrites in an Al-Si eutectic. The green line in Figure 4 corresponds to the AlSiMg alloy and the blue line the AlMgSi alloy. It can also be seen that the two alloy groups chosen in this study are hypoeutectic alloys. The lower amount of Si in the AlMgSi alloy results in a solidification start at a temperature of ~650 °C. The AlSiMg alloy has a Si content more close to the eutectic, which decreases the temperature for solidification start to ~600 °C. So based on the Si content, the difference for solidification start for the two alloy groups should be around 50 °C.

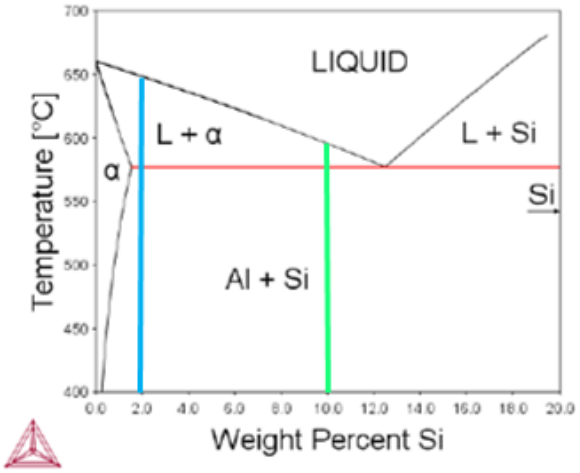

Figure 4. Phase diagram of Al-Si.

The iron (Fe) content is used in conventional HPDC alloys to reduce the tendency for die sticking or soldering [1]. The Fe content can be around 1.3 wt. % (A380 alloy). However, the high Fe content promotes formation of brittle Fe rich phases such as β-Al_5FeSi, which decrease the ductility and elongation [9].

To avoid the brittle phases due to Fe content but still acquire an alloy that prevents die sticking, the Fe content can be compensated with addition of manganese (Mn). The Fe content should be kept as low as possible to avoid brittle Fe rich phases due to detrimental effects [10]. An addition of Mn at Mn:Fe ratio ~0.5 will reduce the β-Fe phase and promote α-phase resulting in an improvement in ductility [11].

Magnesium (Mg) is an element that provides strength to the aluminum alloy by formation of precipitates together with silicon (Mg_2Si). The alloy gets its strength through precipitation, which increases during a heat treatment process. Strength could also be achieved through transformation of the brittle β-Al_5FeSi phases into $Al_8Mg_3FeSi_6$ with an Mg content up to 0.5 wt. %, and above this level no increase in strength will be achieved after T6 heat treatment [12].

2.4 Die material

HPDC is permanent mold manufacturing process. This means that several parts are cast in the same mold, which gives the product its final shape. These molds or dies are usually complex and expensive and in order to have a cost efficient production, they need to last for a long time. Today the die material used for HPDC are made of a special type of steel called hot work tool steels, AISI H. These steels are made to withstand combinations of pressure, heat and abrasion. The tool steels are used in a hardened and tempered condition [13]. Hot strength, ductility, toughness, creep strength, thermal conductivity, temper resistance and low thermal expansion are the fundamental properties for the hot work tool steels [14, 15].

Hot work tool steels needs to maintain its properties at high temperatures, which require having an increased temper resistance so a suitable strength could be obtained after tempering at 550-650 °C. Secondary hardening reaction are a method characterized by precipitation of alloy carbides. Carbide forming elements such as chromium, vanadium and molybdenum precipitate as fine alloy carbides, which increase the hardness and delay the softening when the steel is subjected to a high temperature [13].

2.5 Failure mechanisms in HPDC

The most common failure mechanisms that occur on the die for HPDC is thermal fatigue, also known as heat checking. Thermal fatigue results in a crack network that forms on the die surface, which results in surface marks and flaws on the cast parts, see Figure 5. Since the casting cycle is rapid, the die will be exposed to a thermal variation due to cyclic heating and cooling. This variation in temperature will result in high thermal stresses that lead to plastic strains on the die surface in each production cycle. After a number of production cycles, failure will occur on the die surface [16]. As the numbers of production cycles increases, the crack will start to propagate as a function of number of cycles resulting in a fatigue fracture.

Figure 5. Thermal fatigue on the die (left) results in surface flaws on the casting (right)

Thermal fatigue is strongly dependent on the thermal variation in the die. In Figure 6 a schematic is presented showing the different steps which lead to this phenomenon. In the first step, molten metal is injected rapidly into the closed dies. The die surface becomes heated due to the transfer of the molten metal into the die surface. The heat transfer depends on temperature difference between the die and the molten metal and the heat transfer coefficient. The die surface will try to expand but the cooler die material underneath resists the expansion, which results in a compressive stress layer [17, 18]. Solidification occurs rapidly as the molten metal enters contact with the die cavity. The heat is then removed via conduction from the die surface through the tempering channels.

When the metal has solidified, the second step enters, and the two die halves open. During the opening, the cast part is ejected by the plunger and the ejection pins. The die halves will now be exposed to surrounding air, resulting in some heat lost as the tempering channels continue to transfer the heat in the die.

The third step is spraying of a cooling media and lubricant, which increase the heat removal. Since the spraying is applied on the die surface, it increases the temperature variation significantly. The surface will cool more quickly than the material underneath which results in residual tensile stresses [19].

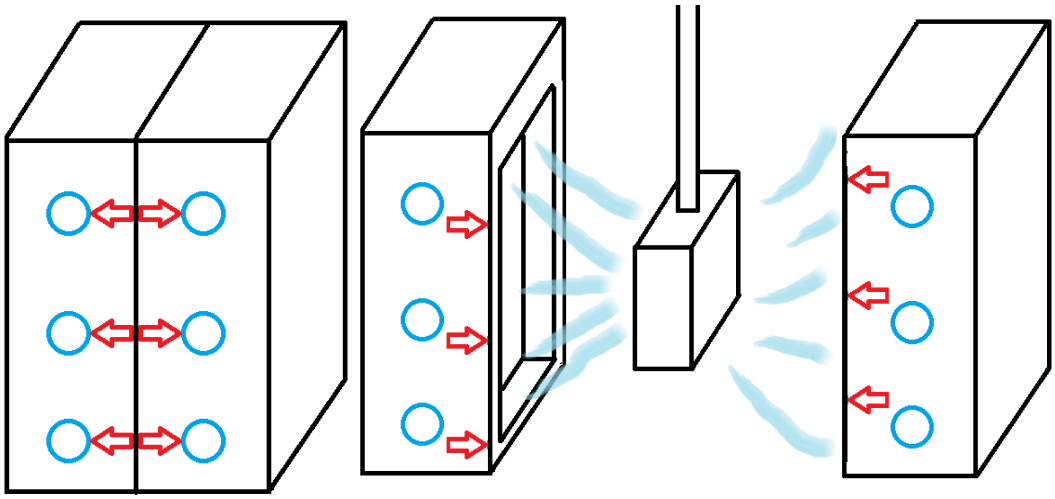

Figure 6. The heat removal in step one and three.

In order to understand how the die material reacts when subjected to thermal fatigue, it is important to know the surface temperature at the different process steps. Literature review has shown that investigations by using thermocouple in order to measure surface temperature have been successful. Persson [20] have investigated die temperature for HPDC of brass and based on his result he estimated that the highest die surface temperature to be 520 °C. Norwood et al. [21] measured the die surface temperature for Al-HPDC with a pouring temperature of 750 °C and a cycle time of 20-24 seconds. The result showed that occasionally the die temperature reached over 450 °C but were typically between 400-450 °C. The temperature drop from pouring temperature to die temperature could be explained due to a skin effect. In addition, a significant amount of heat is removed by the shot sleeve during injection. When the molten aluminum is injected into the die cavity, a skin is formed with impact on the die and the cooling occurs so rapidly that the die surface never reaches the temperature of the aluminum [22, 23].

Soldering is a failure mechanism that often attacks the die during a die casting process. The mechanism is that molten aluminum sticks on the die and solidifies due to diffusion between iron atoms from the die and aluminum atoms from the molten metal, see Figure 7. Between the iron and the aluminum, intermetallic phases will be formed with higher iron content closer to the die material. The result will be that the aluminum will remain on the die after ejection of the cast part, which will have surface flaws and will not be of the right dimension. One of the most important variables in promoting soldering is temperature at the die surface. With increased temperature, the activity of surface atoms, diffusion coefficient and reaction rate will all be increased. The result will be that die soldering will occur earlier and progress faster. The increased temperature could also temper-back the die surface, which softens the surface and promotes soldering in form of adhesive wear. Critical areas in the geometry where soldering can form is in the regions prone to hotspot. Typical hotspot regions are where molten metal is surrounding a piece of the die material. These areas will substantially increase in temperature due to the heat transfer from the molten metal [2].

Soldering behavior is also affected by alloy composition as demonstrated by Kajoch et al. [24], who tested soldering tendencies of several aluminum alloys using a friction welding method. The result showed that Al-Mg alloys had higher soldering tendency than hypoeutectic Al-Si alloys while eutectic Al-Si alloys had lowest soldering tendency.

Soldering could be affected significantly by the level of iron in melt, i.e., by adding some amount of iron into the aluminum alloy soldering could be reduced. This is because iron slows the growth of intermetallic layer [25]. The solubility of iron in hypoeutectic Al-Si alloys is between 2-4 % at the casting temperature. When the aluminum alloy come in contact with the die, surface reaction occur which drops the solubility level to 1-2 %. The eutectic reaction for Al-Fe-Si occurs at ~0.8 wt. % iron, and, an addition of iron above 0.8 % avoids the eutectic reaction and reduce the occurrence of soldering [26].

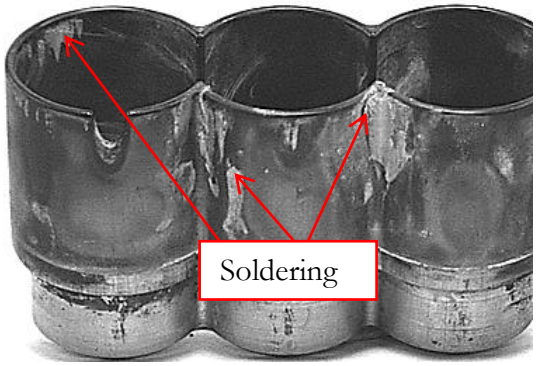

Figure 7. Soldering on a HPDC insert.

Erosion is another common failure mechanism in HPDC and appears often close to the gate in the die cavity. The failure mechanism occurs when molten metal injects with high velocity into the die, which causes erosion wear. The wear process might have different root causes, although, it is commonly accepted that with lower casting temperature erosion wear increases. This is due to the solid fraction and the amount of solid particles in the melt that increase the erosion wear [26]. The gate velocity of the molten metal also have a significant effect on erosion. In comparison with squeeze casting, which has a much lower gate velocity than HPDC, erosion is known to be a less significant factor [2].

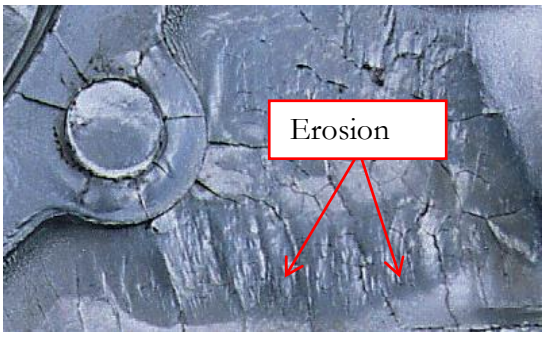

Figure 8. Erosion at the die cavity.

2.6 Simulation

To evaluate what type of failure mechanism might occur during HPDC of AlSiMg and AlMgSi alloys, simulations in MAGMAsoft can be performed. MAGMAsoft is a simulation software that uses finite difference method as solution method. The simulation is solved by discretizing the computational model into a finite number of control volumes during the meshing of the model. The amount of control volumes determines the accuracy of the simulation, which is also in conflict with the computational time. MAGMAsoft is a specialized software for casting simulations, which can simulate most but not all phenomena. Heat and mass transfer is solved by rectangular grid, which is reflected by the cubes on other side of the model. Result of the simulation is then received by filling in the

die and casting related features like velocity, turbulence, hot spots and stresses [27]. It is worth mentioning that simulations are always a simplified way of showing the reality in form of a model.

To evaluate die life based on thermal fatigue, the variation in surface temperature could be measured for the two alloys. The surface temperature is used to determine the stress, which then is applied to a fatigue predication model. In MAGMAsoft 5.4, a die life module is available which uses thermal stresses in the die for the calculation of die lifetime. During injection, compressive stresses will arise on the surface. When the die opens after injection, tensile stresses will arise due to spraying. Therefore, during one production cycle there will be a harmonic oscillation due of the thermal stresses. However, the temperature will increase gradually after some amount of cycles and the potentially stress amplitude. From the oscillating stresses, an amplitude will be attained- σ_A. If the stress amplitude increases, the number of cycles will decrease, the result will be plotted in a Wöhler curve with stress amplitude on the Y-axis and number of cycles on the X-axis.

$$\sigma A = 0.5(\max tensile\ stress - minimum\ compresive\ stress)$$

Since the die life module only uses thermal stresses in the die, in the form of maximum principal stress and minimum principal stress, chemical reactions such as erosion and soldering will not be taken into account. However, areas in the die can be identified to be susceptible to the failure mechanism of erosion and/or soldering by activating the pre-defined criteria in the module, but these cannot be plotted or extended to predicted die life.

Both erosion and soldering are failure mechanisms, which are based on chemical reaction or a thermal reaction. Therefore, they are of high interest when comparing the two chosen aluminum alloys. Soldering is a failure mechanism based on chemical reaction, which can be predicted in MAGMAsoft by localized hotspots. In MAGMAsoft, hotspots can be localized during the casting process [2]. These hotspots may then transform to die soldering when simulating the permanent mold during the casting process. The scale unit for soldering is [s] and stands for the time that die/metal interface is above a critical temperature for soldering to form. Higher value for time and temperature indicates an increase tendency for soldering.

Erosion is substantially affected by the design, which determines the gate velocity as a critical parameter and evaluation of the same can henceforth be performed in MAGMAsoft by locating where in the design. The gate velocity will be increased to reach a risk value. The erosion calculation result in a non-dimensional number that describes how big the erosion damage are at each particular place of the die. The product of characteristic velocity and time defines the reference erosion damage conditions. The erosion damage caused by the action of the melt with reference velocity over the reference time onto the die. As a result, each volume of the die has a number that is a ration of the actual erosion damage to the reference damage.

2.7 Mechanical data

In order to perform the MAGMAsoft die life simulation, data from fatigue tests in form of a Wöhler curve from the die material needs to be loaded into the software. High cycle fatigue is a damage that occurs when cyclic or fluctuating strains at nominal stresses with a maximum value, which is lower than the yield strength of the material. A fatigue crack could only be initiated and propagated if three simultaneous conditions are applied. The

three conditions are presence of cyclic stress, tensile stress and plastic strain. Plastic strain initiates the crack due to cyclic stress and the tensile stress promotes the crack propagation [28].

Fatigue properties can be divided into three different diagrams, they are:

- Stress cycle (S-N) curve
- Strain cycle (ε-N) curve
- Crack growth rate (da/dN-ΔK)

The stress cycle also known as stress life is distinguished by the S-N curve or Wöhler curve. The Wöhler curve shows the number of cycles that are needed in order to acquire fracture of the material at a certain stress level. There are several important parameters needed in order to distinguish fatigue life shown in equations 1-4 [29].

- Stress range, difference between maximum and minimum stress:

$$\Delta\sigma = \sigma_{max} - \sigma_{min} \qquad \text{(eq. 1)}$$

- Mean stress, average of maximum and minimum stress:

$$\sigma_m = \frac{\sigma_{max}+\sigma_{min}}{2} \qquad \text{(eq. 2)}$$

- Stress amplitude, is the half stress range:

$$\sigma_a = \frac{\Delta\sigma}{2} \qquad \text{(eq. 3)}$$

- Stress ratio, ratio between minimum and maximum stress:

$$R = \frac{\sigma_{min}}{\sigma_{max}} \qquad \text{(eq. 4)}$$

A Wöhler curve is normally obtained from rotation bending test performed at room temperature. The test producing tensile and compressive stresses which are cyclic between a maximum tensile stress and maximum compressive stress. The results of the fatigue failure are then plotted as stress amplitude, maximum stress or minimum stress to number of cycles until failure by using a logarithmical scale. The S-N curve shows the number of cyclic stress that the material can endure before failure occurs depending on the stress amplitude. For steel, the curve becomes horizontal at a limit of stress. Below the stress limit, also known as the endurance limit the material can be exposed to an infinite number of cycles without failure [30].

Since the load for thermal fatigue is based on a difference in temperature, the variation of compressive and tensile stress will be caused by the temperature variation. Limited amount of studies have been found in order to correlate thermal fatigue into an S-N curve for a suitable hot work tool steel die material. Denis Delegnes made a thorough study on fatigue of an AISI H11 hot work grade, which is commonly used as die material for HPDC. The doctoral thesis focused on fatigue behavior at the transition between low cycle fatigue and high cycle fatigue. Low cycle fatigue is normally distinguished with failure after less than 10^4 cycles and is dominated by plastic strain. High cycle fatigue is dominated by elastic strain. One important effect that Delegnes focused on were test temperature. The result

of the temperature effect showed that failure occurs between 4.000 and 50.000 cycles for most of the samples. In order to get a stress life relationship to plot an S-N curve at different temperatures, stage Basquin's model had been used (equation 5) where σ_a is alternative stress, N is fatigue life, C_e and ϱ are model parameters. An increase in temperature resulted in a decrease of stress level and cyclic softening intensity, which shortens lifetime, see Figure 9 [31, 32, 33].

$$\sigma_a = C_e * N^{\rho} \qquad \text{(eq. 5)}$$

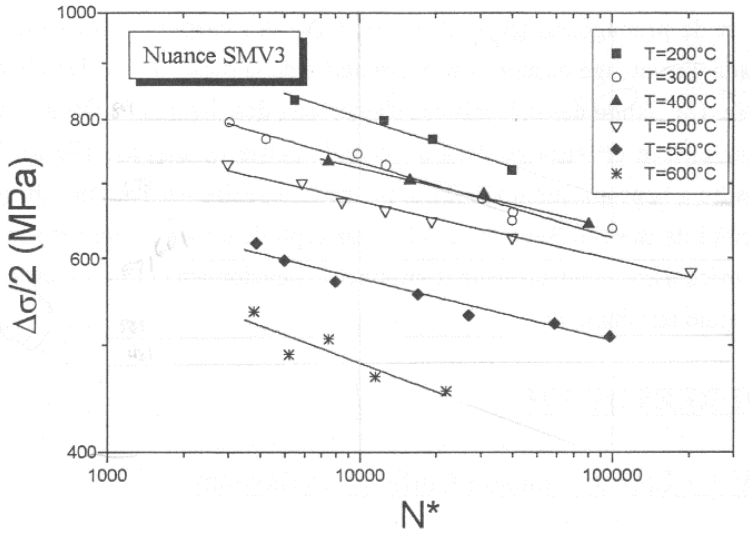

Figure 9. Basquin's model fits stress life data from 200 - 600 °C [31].

3 Method

The aim of the thesis work was to obtain a good understanding of the HPDC alloys and how it might affect die life through simulations. Some of the potential failure mechanisms regarding temperature and chemical effect have been handled in the theoretical background. The method chart can be seen in Figure 10.

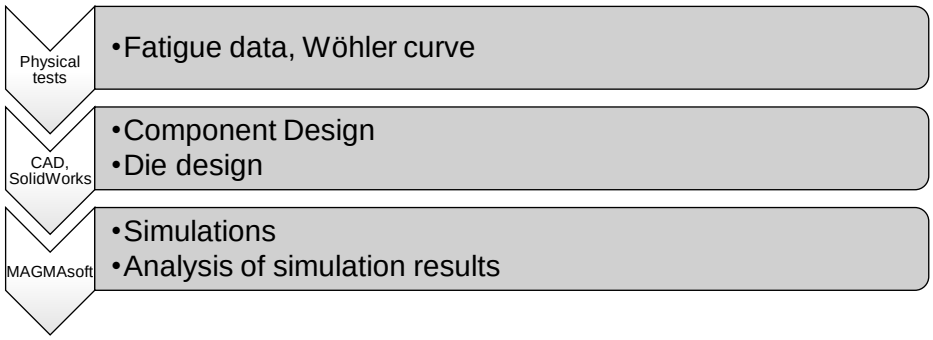

Figure 10. The method chart.

3.1 Literature review

In order to carry out the simulation with process parameters close to what is used in the foundry industry, literature review has been conducted in order to gather information. The focus of the information gathering has been on creating an understanding of the common die failure mechanism, research where temperatures have been measured in different process steps, fatigue experiments at elevated temperature and material data for the two aluminum groups.

3.2 Die material data

The material of simulation interest during the casting cycles were the die tool steel. Based on the availability of suitable fatigue data from previous research AISI H11 were selected as die material, a commonly used die material for HPDC. Fatigue data were found during literature review, where fatigue testing had been performed at different temperatures, see Figure 9. The curve performed at 550 °C were selected due to the measured range between initial temperature and die cavity temperature [21].

3.3 CAD design

The cast component needed to be made with a design freedom so that the encountered loads could be supported. To carry these loads, ribs were applied in the component design. The component were designed in the CAD software SolidWorks with a dimension of 300x150 millimeters. Figure 11 and 12 shows the cast component with gate, runner and biscuit.

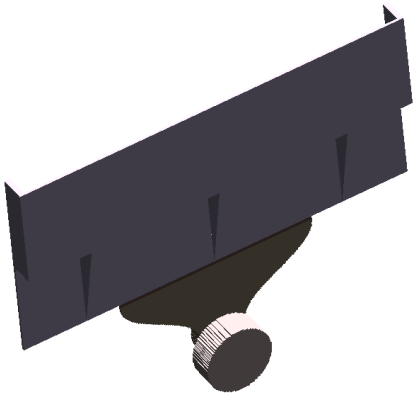

Figure 11. Casting: component, gate, runner and biscuit side shaped by cover die.

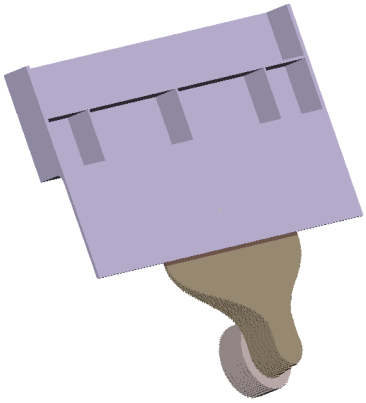

Figure 12. Casting: component, gate, runner and biscuit side shaped by ejector die.

The die design has been carried out in SolidWorks for the two die cavities. Holder blocks were drawn directly in MAGMAsoft, and spray, tempering channels, gate and runners were imported from MAGMAsoft database. The assembly of the parts was performed in order to receive a split line in the center of the biggest mass for the cast component. Tempering channels were used with a defined distance of 25 millimeters from the cavity surface, see Figure 13 and 14.

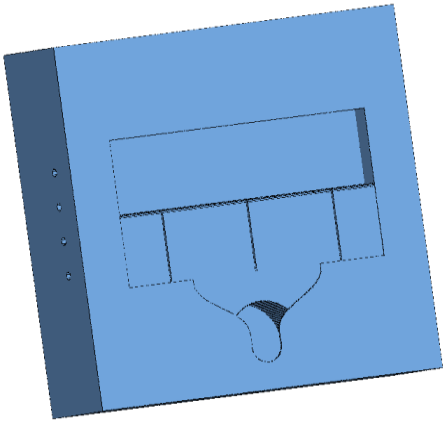

Figure 13. Cover die design.

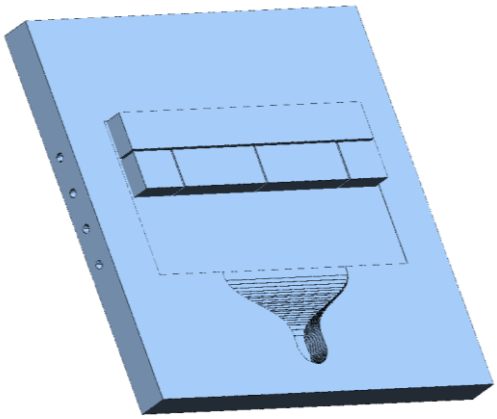

Figure 14. Die design, ejector die to be simulated of stresses.

3.4 Simulation set up

Table 3. Simulations performed with the change of variables.

Simulation	Alloy	Initial temperature	Die Spray	Die tempering
1	AlSi9MgMn	640 °C	X	X
2	AlMg5Si2Mn	640 °C	X	X
3	AlMg5Si2Mn	660 °C	X	X
4	AlSi9MgMn	640 °C	X	
5	AlSi9MgMn	640 °C		X
6	AlSi9MgMn	640 °C		

Table 3 shows the number of simulations with the change of variables performed. The simulations are divided into two sets; simulation set 1 consisting of 1-3 refers to variation

of cast material and initial temperature. Simulation set 2, simulation 4-6 refers to variation of process parameters with constant variables of cast material and initial temperature.

The first set of simulations were performed in order to compare the two aluminum alloys. The simulation setup is fixed for the two alloys with only variation of casting material and initial temperature. A third simulation were also conducted with initial temperature as constant and the only variable being casting material in order to evaluate the potential solidification time and heat contact time to the die.

The second set of simulations were performed in order to correlate the two cooling systems of die spray and tempering channels. The simulations were performed with AlSi9MgMn alloy with fixed initial temperature. Simulations were performed three times, one with only spray as cooling, one with only tempering channels and one with no cooling system.

First step for the simulation setup was to import geometry of the cast part and the two die halves from SolidWorks with STL format. Simplified holder blocks were created directly as 3D volumes in MAGMAsoft. Spray head, gate system and shot chamber system were imported from MAGMAsoft database. Spray head were placed so that both die halves were sprayed from the same distance when the die is open. Shot chamber and gate system were assembled in order to fill the component from the bottom. Tempering channels were created in MAGMAsoft in shapes of four connected tubes at each die half with dimensions of Ø 8 x 400 mm. For movable die, one macro were created with the entire movable components placed inside. The macro helps the software to understand which component belongs to which die half and therefore should move when die is opened and closed. The component placed in the movable macro were ejector die and holder block for the ejector die.

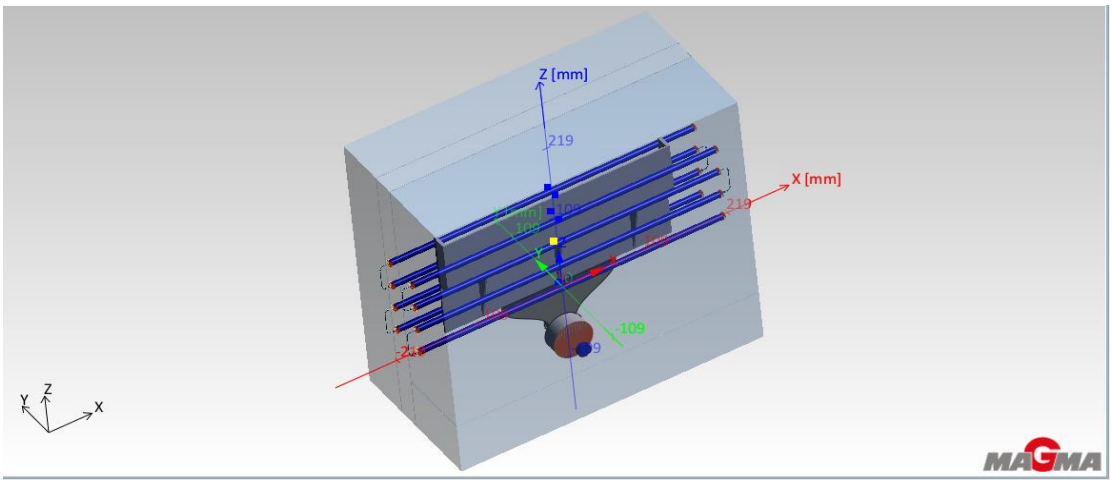

Figure 15. The assembly of the casting system.

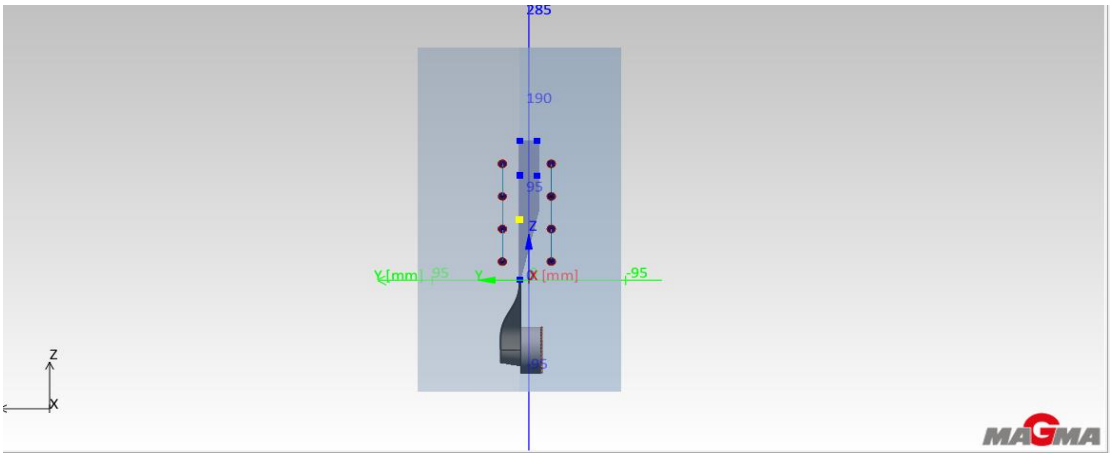

Figure 16. The assembly of the casting system.

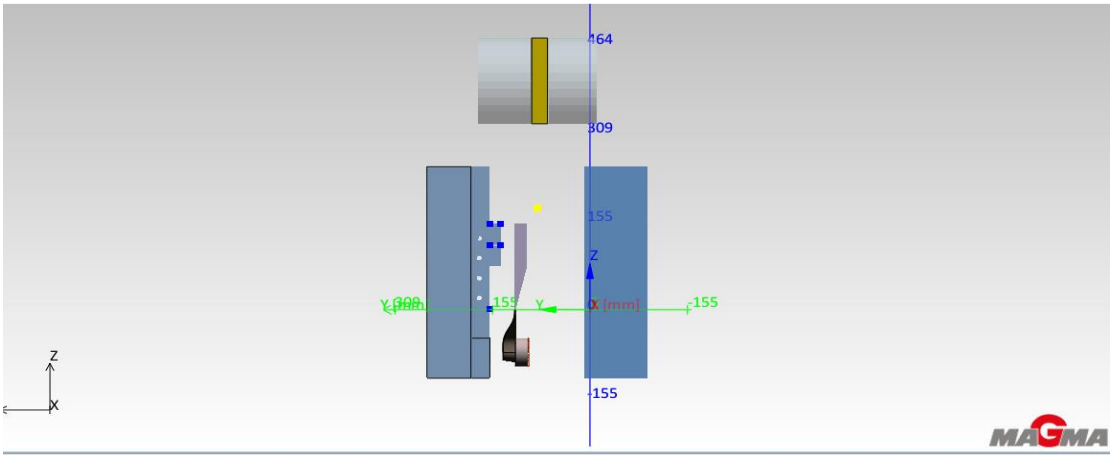

Figure 17. Die open with spray head.

The second part of the simulation set up is to consider meshing. MAGMAsoft is based on finite difference method, which discretizes the part into a finite number of control cubes, which are referred to as cells during the meshing. There are two options for mesh criterion on MAGMAsoft; manual based on multiple parameter sets and automatic based on number of elements. Manual meshing gives more control freedom for the different components in the assembly setup, so that each component can be meshed with individually defined mesh parameters.

Components can also be grouped together where meshing can be performed with a common setting assigned to the specific group. Automatic meshing is performed through selection of a certain number of elements and is preferable when a few amount of components is used and all should be evaluated. Since the assembly setup contains several components, only the ejection die will be evaluated using manual meshing.

The multiple parameter sets contained of six groups: mold, shot chamber, tempering channel plunger, runner and casting.

Cartesian mesh parameters were; (x, y, z) geometry filter, (5, 5, 5) for mold, shot chamber and tempering channel plunger, (1, 1, 1) for tempering channel, (2, 1.5, 2) for runner. Subdivisions, (3, 3, 3) for all groups except of tempering channel which were (6, 6, 6). Minimal element size, (0.25, 0.25, 0.25) for mold, (5, 5, 5) for shot chamber and tempering channel plunger, (1.33, 1.33, 1.33) for tempering channel and (2, 2, 2) for runner. Coarsening threshold, 3 was used in the mold, 6 in the tempering channels and 5 in all

other. Coarsening loops, 3 were used in the mold, 1 in the tempering channels and 0 for all other. Maximum aspect ratio of an element, 3.5 for mold, shot chamber and 3 for all other. Maximum length of neighboring elements, 2 for mold, shot chamber and 1.66 for all others. The casting were performed with equidistant, element dimensions 0.5, 0 number of coarsening loops and 5 coarsening threshold, see Table 4 and 5.

Table 4. Mesh parameters.

Mold	X	Y	Z
Geometry filter	5.0	5.0	5.0
Subdivisions	3	3	3
Minimal element size	0.25	0.25	0.25

Table 5. Mesh parameters.

Maximum length ratio of neighboring element	Maximum aspect ratio of an element	Number of coarsening loops	Coarsening threshold
2	3.5	3	3

The meshing received 57,849,640 numbers of cartesian cells see Figure 18.

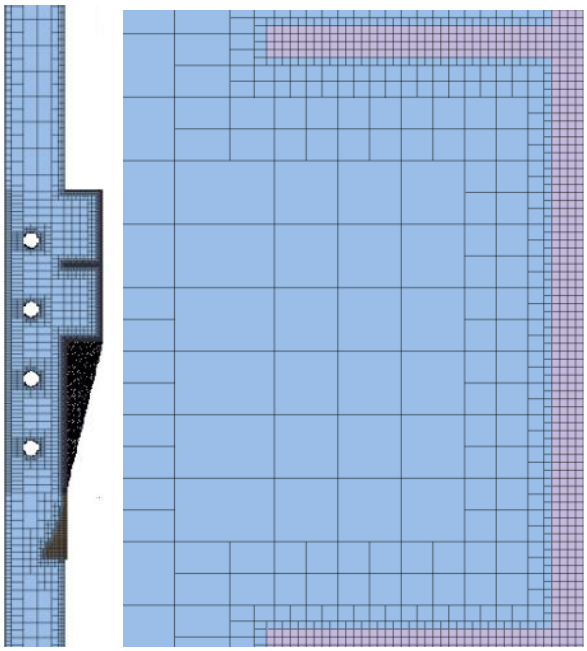

Figure 18. Cross-section of the mesh, blue is ejector die and grey is casting

3.5 Definitions

In definition navigator, all process information are entered such as materials, heat transfer, casting process and result. The first part in the definition is related to materials. AlSi9MgMn corresponding to Silafont-36 and AlMg5Si2Mn corresponding to Magsimal-59 were selected from MAGMAsoft database as casting materials. Initial temperature for AlSi9MgMn was 640 °C and 660 °C for AlMg5Si2Mn.

The die material for ejector die, cover die and plunger were AISI H11 selected from MAGMAsoft database with initial temperature of 150 °C. The material properties in the form of Wöhler curve were taken from the database. This data is highly temperature dependent where an approximation has been made by applying a quadratic formula with the KT coefficient. Based on this, a maximum oscillating stress of 925 MPa and unlimited endurance of 370 MPa have been obtained at a temperature of 480 °C. The minimum number of cycles is considered as 100 and a maximum 1,6 million is used for the prediction of macroscopic cracks. Since initial temperature for the two alloys varies between 640 °C and 660 °C, a possibility for a local temperature to above 480 °C is assumed and die life values below 1000 cycles is expected to be rare. Therefore three values from Basquin's model at 550 °C were added to the linear curve from 1000 to 100 000 cycles, see Figure 19. Unexpectedly, the three data points showed to be very close to the data obtained at 480 °C. Cooling medium parameters were also imported from MAGMAsoft database with water-flow for tempering channel and cooling medium for tempering of plunger at an initial temperature of 20 °C.

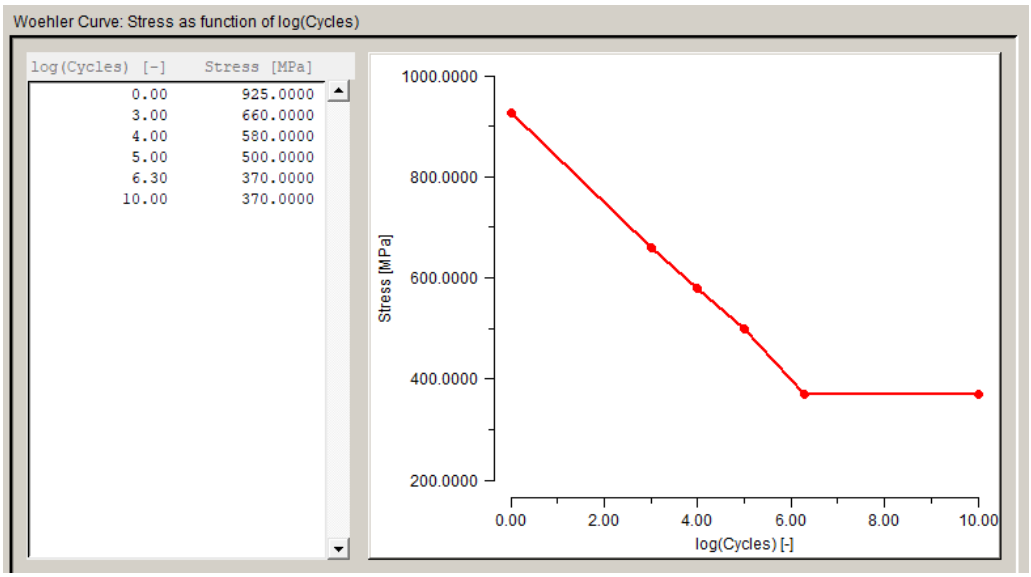

Figure 19. Wöhler curve

Critical soldering temperature were set as default to 558 °C and critical filling velocity for mold erosion to 60 m/s.

The heat transfer for the simulations was then defined. Heat transfer coefficients needs to be defined for all neighboring materials where heat is transferred. The heat transfer coefficient between two materials is strongly dependent on the surface contact. The surface contact between two materials are affected by surface roughness or potential flaws at the surfaces of the materials. Consequently, when an interface is created between the two materials the potential of heat transfer will have an effect on surface quality.

The heat transfer coefficient between the molten aluminum alloys and the die materials were set to default of constant 10 000 W/m^2K. Between the die halves, a constant heat transfer coefficient of 3 500 W/m^2K were used. Between the tempering channels and the die materials, a standard heat transfer coefficient were selected from MAGMAsoft database. A constant heat transfer coefficient of 2 000 W/m^2K were selected between the plunger and the die material.

The next part to be defined is the casting process. Casting process was divided in several steps of one cycle. First, the number of heating cycles were selected to 12. This is the number of cycles that are performed to heat up the die and casting system to a steady production temperature. After the 12 heating cycles, one production cycle was selected. In the cycle control, the casting process parameters are defined for four process steps, preparation, filling, solidification and cooling and die tempering.

After the definition stage, the preparation step needs to be performed for simulations. The preparation step consists of four sub-steps, die preparation, place inserts, die close and dosing. Die preparation are the first step of the casting cycle and consists of die spraying. The spray system were created during the assembly. In the die preparation, spraying was set with a total time of 8 seconds. 4 seconds when the spray head moves 350 millimeters down between the die halves and 4 seconds to move back to the origin position. Important to note that die spray were only applied over the die cavity and not the gate area. Those simulations that were run without spraying had the sub-step die preparation deactivated.

The model had no loose cores or replaceable inserts so the sub-step place insert was deactivated. Die close was set to take place 12 seconds after die preparation starts. No shot chamber were used and therefore the dosing definition were deactivated.

For the filling step, a shot curve needs to be optimized based on the casting volume and process parameters. The function shot curve calculator in MAGMAsoft were used, the function calculates the total casting volume from the mesh, which was 226.35 cm^3. The locking force, which keeps the two die halves together, were calculated to 3107.1 kN based on specific pressure of 400 bar and projected area. MAGMAsoft shows warnings if a safety factor of 30 % is not added on the result of minimum locking force, this resulted in a minimum locking force of 4039.23 kN. Machine MAGMA/Demo_700, which provides a locking force of 7000 kN, were chosen from MAGMAsoft machine database which fulfills a safety factor of 30 %.

Shot chamber length was set to 300 millimeters, plunger diameter to 50 millimeter and biscuit thickness 19.53 millimeter. The plunger position were set to 35 millimeter when the pour hole is covered. Oven temperature based on initial temperature of 640 °C were set as default at 741 °C.

The filling consists of two phases, in the first phase the piston should move slowly in order to reduce the amount of air in the shot chamber and avoid turbulence. A constant acceleration with final plunger velocity of 0.2 m/s were set. The second phase is called the acceleration phase and are applied when the melt reaches the gate, the piston should now fill the cavity with force. Maximum machine acceleration of 200 m/s^2 were set to start when the plunger had moved 200 millimeter to a velocity of 4 m/s had been reached. The maximum filling time were set to 30 ms, characteristic wall thickness 2 millimeter, gate area 2.24 cm^2 and the maximum metal velocity at the gate for the second phase got to 34.98 m/s.

The solidification and cooling until eject step consists of five sub-steps; intensification, local squeezing, die open, eject casting and removal time. Intensification is an applied pressure by the plunger that compensates for the solidification shrinkages that reduces the volume of the casting. Starting pressure was set to 1 bar and the setup time 0 seconds for a working pressure of 600 bar. Reduction starts 20 seconds after beginning of solidification and cooling until eject, pressure reduction time was set to 0. Local squeezing was not used and therefore deactivated. The die opened 35 seconds after beginning of solidification and cooling until eject. Eject casting and removal time were both deactivated.

In the die, tempering step process parameters regarding the tempering channels can be changed and optimized after the users need. For this study, the tempering channels were set to work with a continuous flow during the whole cycle except for the simulation without tempering channels, then the die tempering step were deactivated.

After the definition of materials and process related information, the results to be obtained from simulations are to be defined. In the result definition, selections of how the result should be determined and displayed are made. Stress result is of interest for die life and were defined individually for the different process steps. For preparation, stress result should be stored every 0.1 seconds from 0 to 8 seconds and every 0.5 seconds from 8 to 12 seconds. For filling stress result and result dependent on process progress should be stored after percent filled every 1 % from 0 to 100 %. Solidification and cooling until eject, result dependent on progress should be stored every 1 % from 0 to 100 % and stress result stored every 1 % from 0 to 100 % plus every second from 0 to 35.

3.6 Analysis of simulation results

The results of die life, soldering and erosion are analyzed in the form of simulation output. Calculation of the highest stress amplitude for each simulation will be plotted in the Wöhler curve. For each die cell, the number of cycles before failure resulting in a die life value and a corresponding location will be compared in a table for each set of simulations. The critical location for each simulation will be shown via a logarithmic scale for crack initiation and the hence determined die life value. To determine which phase in the production cycle is most prone for stress, formation data of maximum compressive stress and maximum tensile stress are of interest. For each set of simulations, the received thermal stresses in the die for one production cycle will be plotted as stress curves. To obtain insight of the heat interface between the aluminum and die materials, maximum temperature in the process material is plotted over time. Curves show the temperature variation of the process material over one casting cycle.

The results of die soldering on the die surface will be expressed based on the length of time that the temperatures at the die/metal interface exceeded the selected critical temperature of 558 °C. The results will be compared in tables for each simulation set and critical locations exposed in the die.

Erosion calculation will be based on a non-dimensional number that describes the local erosion on the die. For each set of simulations, the results will be compared in a table and locations showed.

4 Findings and analysis

4.1 Die life

Highest stress amplitude for each simulation were calculated by the software and plotted against the Wöhler curve in order to obtain the number of cycles before failure. The results are presented in Table 6 and 7.

Table 6. Die life results for alloy comparison- set 1

Simulation	1	2	3
Die life	~94 000 cycles	~38 000 cycles	~15 000 cycles

Table 7. Die life results for comparison of process parameters- set 2

Simulation	4	5	6
Die life	~102 000 cycles	~94 000 cycles	~220 000 cycles

Comparison of the aluminum alloys shows that simulation 3, AlMg5Si2Mn (660 °C) had received the highest stress amplitude and therefore the lowest amount of cycles before failure. A major difference in die life could be seen for the two alloys with the same initial temperature, simulation 1 and 2.

Influence of die spray, die tempering and no cooling showed that the simulation 6, performed with no cooling had gotten the lowest stress amplitude and therefore survived most amount of cycles before failure.

Locations of highest stress amplitude for each simulation is seen in Table 8 and 9.

Table 8. Critical locations for die life, alloy comparison

Simulation	1	2	3
Stress location	Gate	Gate	Gate

Table 9. Critical locations for die life, comparison of process parameters

Simulation	4	5	6
Stress location	Cavity, corner	Gate	Cavity, corner

For all simulations performed with tempering channels, the highest stress amplitude was found in a corner at the gate see Figure 20 and 21. For simulations performed without tempering channels, the highest stress amplitude was located in a cavity corner see Figure 22 and 23.

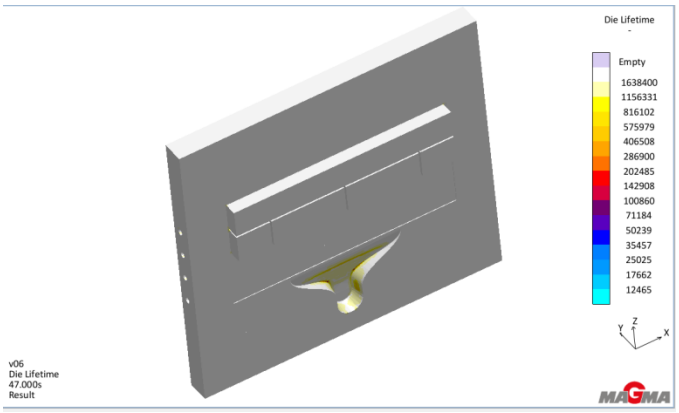

Figure 20. Critical location of die life, Simulation 3

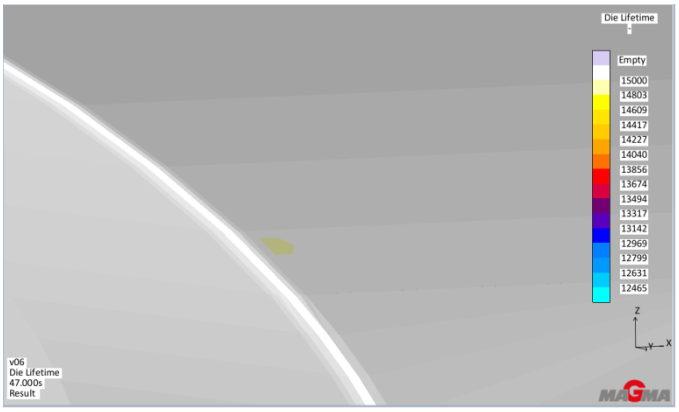

Figure 21. Die life close to the corner of the gate, Simulation 3

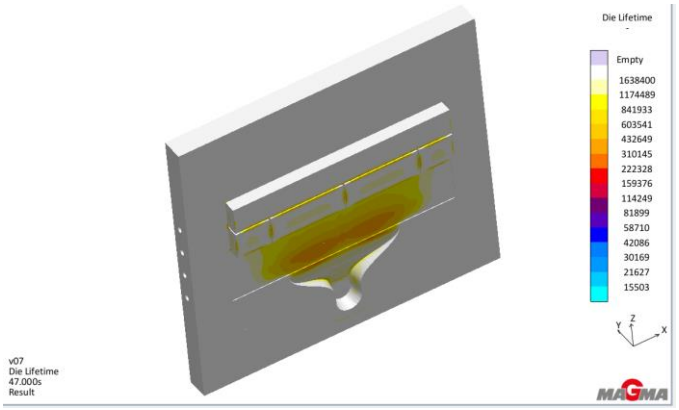

Figure 22. Critical location of die life, Simulation 4 (only die spray)

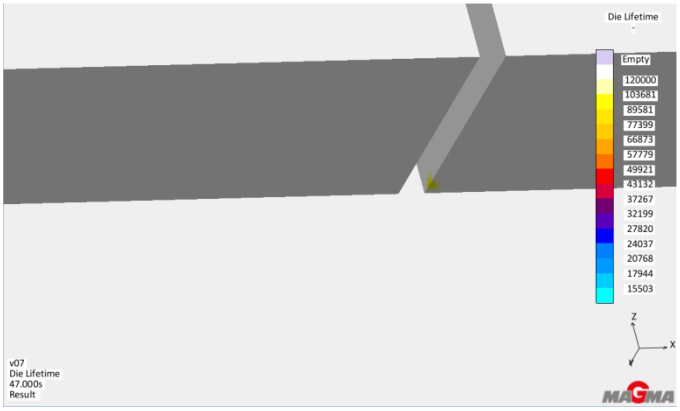

Figure 23. Critical location of die life, Simulation 4 (only die spray)

Table 10, presents additional findings during evaluation, the result shows stress amplitude in cavity considering that gate area is isolated from cooling.

Table 10. Additional findings regarding die life, restricted to the cavity

Simulation	1	2	3	5
Die life in cavity	~658 000 cycles	~998 000 cycles	~778 000 cycles	~600 000 cycles

If evaluation would only be considered in the cavity within the range of die spray and die cooling, comparison of the aluminum alloys shows that simulation 1, AlSi9MgMn (640 °C) had received the highest stress amplitude and therefore the lowest amount of cycles before failure. For simulation 5 performed with tempering channels, the result was a longer die life in the cavity than in the gate.

4.2 Stress Curves

The highest obtained thermal stresses located in the die are plotted over one cycle in form of the specific location with maximum tensile stress and maximum compressive stress. Location of stresses within the die can vary since the curves shows the maximum stress obtained in the die.

Stress curves from the alloy comparison (set 1) simulation are shown in Figure 24. The result shows that the highest tensile stress value were obtained in simulation 1 of AlSi9MgMn (640 °C) during solidification, 47 seconds on the X-axis. The highest compressive stress were similar for all the three simulation but a slightly higher value was obtained for simulation 1, AlSi9MgMn (640 °C) after complete filling, 15 seconds on the X-axis. The highest difference between tensile and compressive stress were acquired after filling for the AlSi9MgMn (640 °C) simulation 1.

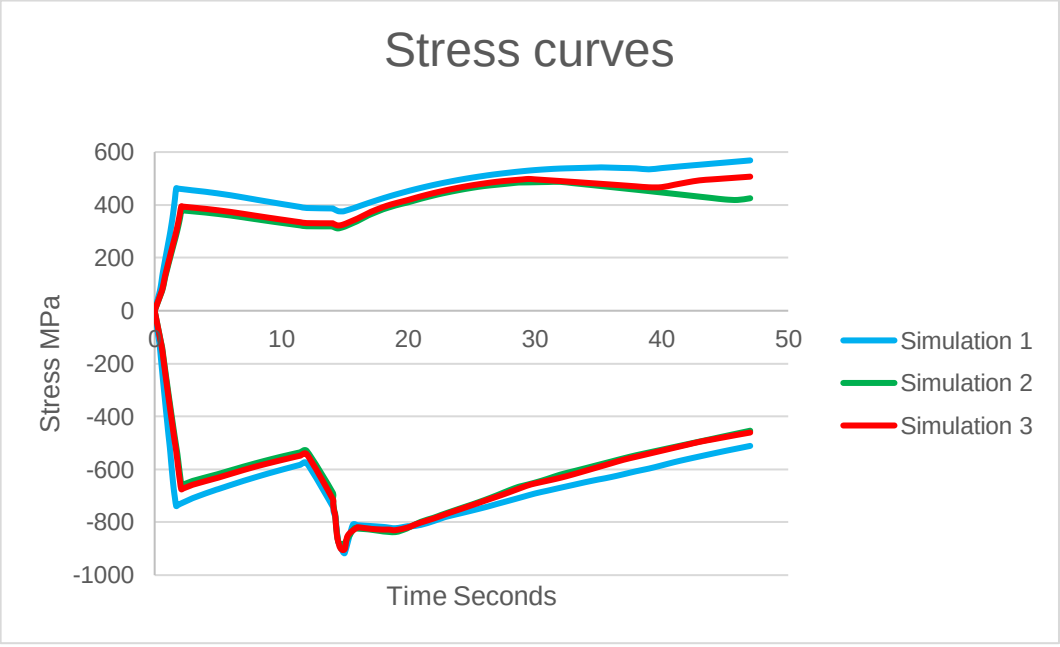

Figure 24. Stress curves, tensile and compressive for simulation 1-3

Stress curves from the simulations of process parameters (set 2) are shown in Figure 25. The result shows that the highest tensile stress value were obtained in simulation 6 performed with no cooling, during solidification where reaches a value above 600 MPa.

The highest compressive stress were acquired for simulation 5 performed with only die tempering channels, after complete filling. The highest range between tensile and compressive stress were obtained during die spray for simulation 4, performed with only die spray.

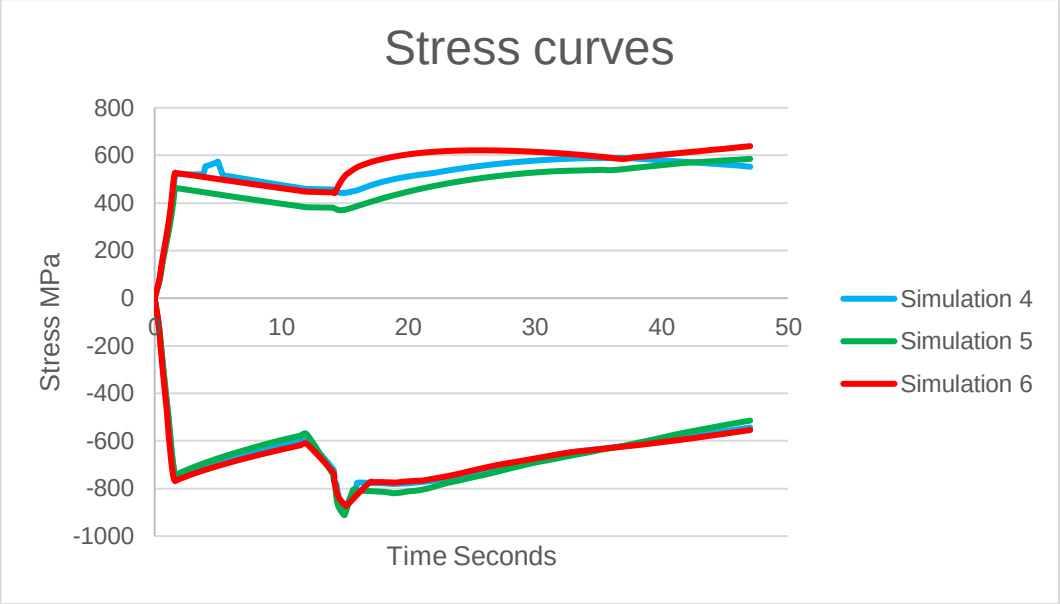

Figure 25. Stress curves, tensile and compressive for simulation 4-6

4.3 Temperature Curves

In order to obtain insight of the heat interface between the aluminum and die materials during a casting cycle, maximum temperature in process material were plotted. Figure 26 to 31 shows the temperature curve of the process material over one casting cycle. In the curves, the yellow line represents the liqudius temperature and the blue solidus temperature. When the red line that represents the maximum temperature of the process material crosses the solidus line, temperature is decreasing rapidly.

The curves for comparison of aluminum alloy (set 1), temperature curves shows a higher temperature difference between highest and lowest temperature for the simulations of AlMg5Si2Mn. It could also be noted that the curve for AlSi9MgMn is held above the solidus temperature for a longer time.

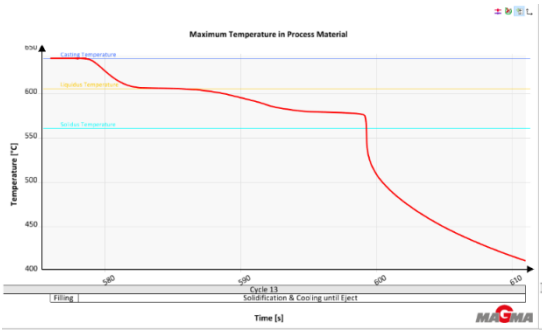

Figure 26. Casting temperature, AlSi9MgMn (640 °C)

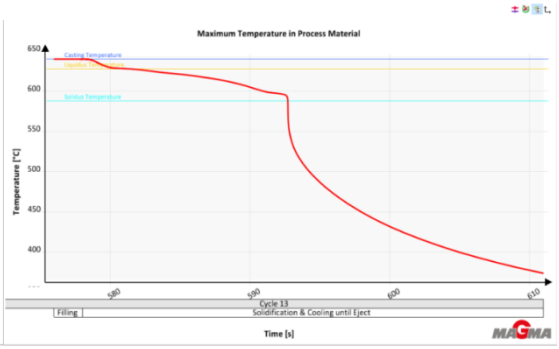

Figure 27. Casting temperature, AlMg5Si2Mn (640 °C)

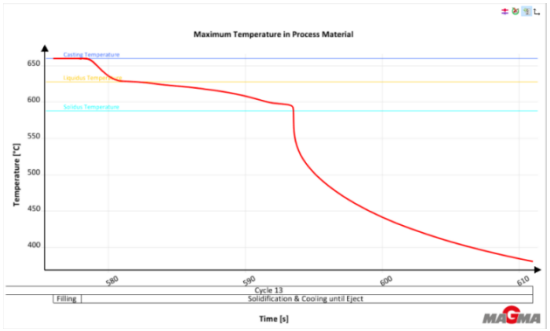

Figure 28. Casting temperature, AlMg5Si2Mn (660 °C)

The curves for simulations of process parameters (set 2), showed that with die tempering the process material cooled faster to solidus temperature.

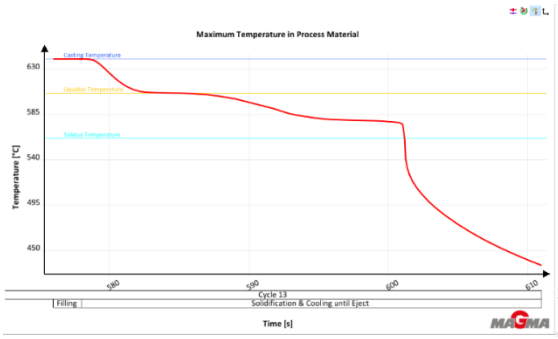

Figure 29. Casting temperature, Only Die spray

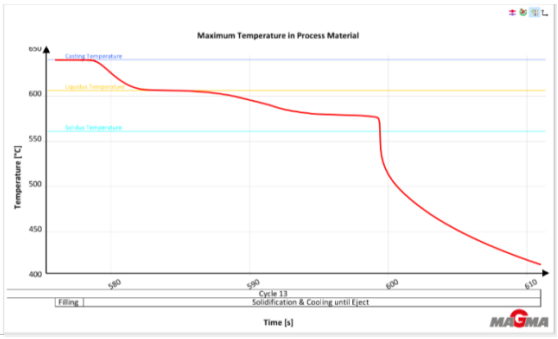

Figure 30. Casting temperature, Only Die tempering

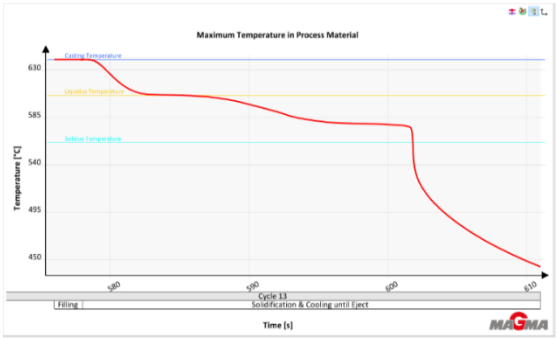

Figure 31. Casting temperature, No cooling

4.4 Soldering

Die soldering results is shown in Table 11 and 12 for each simulations. For comparison of aluminum alloys, simulation 1 AlSi9MgMn had the highest potential for soldering formation with a value of 9.5 s. Comparison of process parameters showed that simulation 6 performed with no cooling had the highest potential for soldering with a value of 12.2 s.

Table 11. Soldering results for alloy comparison

Simulation	1	2	3
Soldering (s)	~9.5	~4.2	~5

Table 12. Soldering results for comparison of process parameters

Simulation	4	5	6
Soldering (s)	~11.4	~11	~12.2

The critical locations of die soldering for all simulations were in the bottom area of the gate system, see Figure 32 and 33.

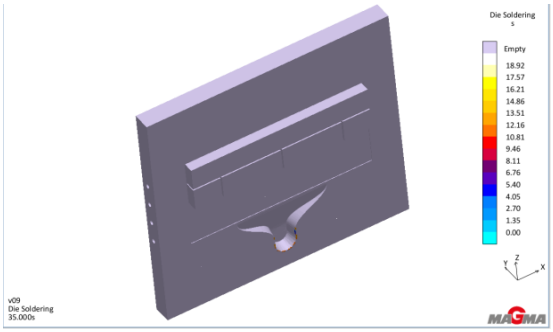

Figure 32. Critical location for soldering, simulation 6

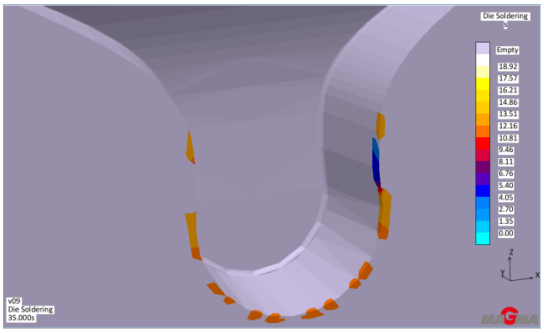

Figure 33. Critical location for soldering, simulation 6

4.5 Erosion

Mold erosion, defined by filling velocity are shown in Table 13 and 14. The result for alloy comparison showed that simulation 2, AlMg5Si2Mn (640 °C) had the highest value for mold erosion. Comparison of process parameters showed that simulation 4 only die spray had the higher value for erosion than simulation 5 and 6.

Table 13. Erosion results for alloy comparison

Simulation	1	2	3
Mold erosion	~0.017	~0.03	~0.019

Table 14. Erosion results for comparison of process parameters

Simulation	4	5	6
Mold erosion	~0.025	~0.016	~0.02

Critical areas for mold erosion characterized by filling velocity is seen in Figure 34 to 37.

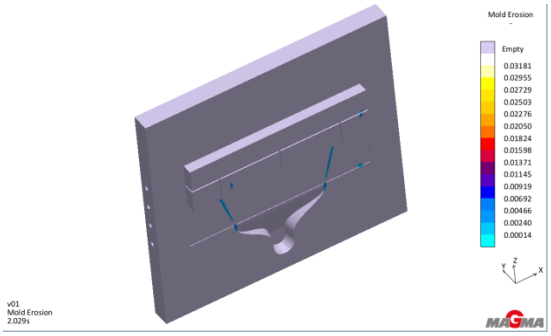

Figure 34. Location of mold erosion, AlMg5Si2Mn (640 °C)

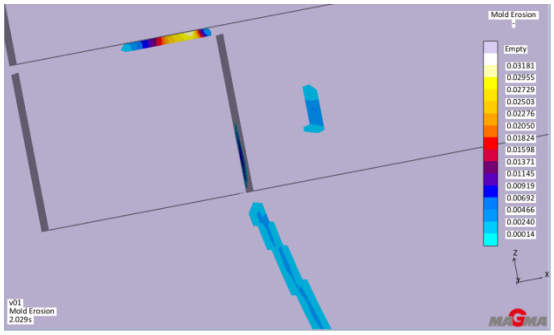

Figure 35. Location of mold erosion, AlMg5Si2Mn (640 °C)

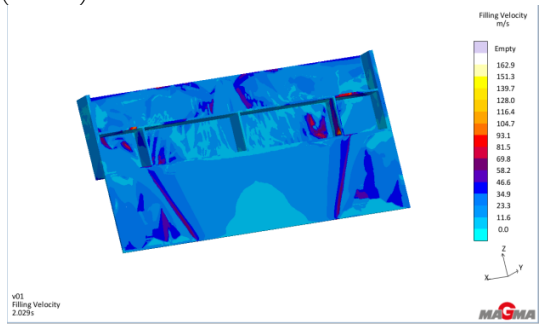

Figure 36. Filling velocity, AlMg5Si2Mn (640 °C)

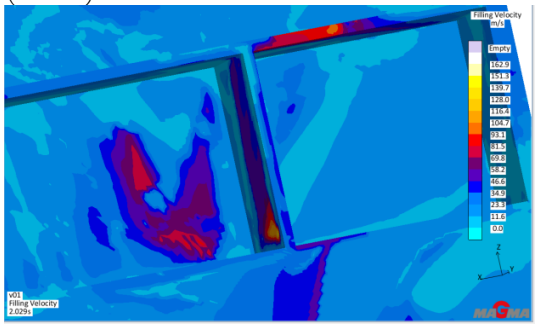

Figure 37. Filling velocity, AlMg5Si2Mn (640 °C)

5 Discussion and conclusions

5.1 Discussion of method

The purpose of this work was to investigate failure mechanism through simulation. The method of the investigation were purely made in MAGMAsoft.

The reality of a casting cycle is very complex where several undefined parameters could influence the result. Therefore, some degree of idealization needed to be taken into account in order to create a mathematical model. The calculation of the mathematical model and the results are then based on the data loaded into the definition and the fine mesh of volume. Since simulation is a simplified visualization of the reality, the accuracy compared to a physical foundry experiment or production cycle will never show a correlation of 100 %. However, the method are a suitable initial experiment to predict die life, which can be taken to a foundry experiment and get a higher reliability of the potential failure mechanism.

In the following paragraphs, each aspect corresponding to sections 3.3 CAD design to 3.6 analysis of simulation results are discussed in the same order.

The CAD models of cast part and die parts were designed in a simplified and symmetric way in order to save computational time but with adequate complexity to create reasonable stresses that may arise in a real HPDC die. The CAD models fulfilled its purpose in order to save computational time and still acquire stresses in locations that could be predicted prematurely. However, to strengthen the research it would be good to use parts that had been in production in a real die. In this way, a more close to field study would be achieved.

The two sets of simulations, comparison of alloy composition including initial temperatures and the effect of cooling processes were selected to receive the data needed to fulfill the research questions in a time efficient way. Additional simulations could have been run with more parameters, resulting in greater data volume for evaluation. However, delimitations were made in order to eliminate data that were non-accurate for the purpose of the work.

The assembly setup in MAGMAsoft were conducted with minimal gaps and overlapping in order to obtain error free simulations. Several setups could be investigated from the assembly like position of spray head, placement and dimension of tempering channel. This would result in a more process-optimized evaluation at the expense of computational time.

Meshing was performed with fine element size in order to get high accuracy. However, finer mesh could been applied but it would consume more computational time. It would be possible to import the ejector die as a single group with finest mesh since it is the only part where stress calculations are evaluated. However, it would not guarantee to get fully accurate result due to the other definition parameter that influence the results.

Material definition for the cast materials were selected from MAGMAsoft database and the result showed high correlation with the data from Rheinfelden in terms of solidification interval. The Wöhler curve data of die material AISI H11 were taken from a fatigue test performed at elevated temperature. This data shows the stress life relationship at the specific constant temperature. However, in HPDC the temperature are not constant and therefore it would be interesting to investigate the possibility to perform a thermal load

based fatigue test. Another parameter of importance for die life is the die material softening. If an AISI H11 grade is exposed to high heat for a longer time, the surface will temper back. When tempering occurs the material surface will soften resulting in a lower fatigue strength and in a thermal load based fatigue test, this parameter will be taken into account and potentially showing a more close to reality thermal fatigue die life curve.

In the heat transfer definition, the heat transfer coefficient were set as default between the molten aluminum alloys and the die materials to constant 10 000 W/m^2K. The reason for a constant HTC were in order to mimic reality inclined results of ~100 000 cycles. Trials were performed with temperature dependent HTC which goes from 8000 to 4000 W/m^2K in the solidification interval. The result showed an abnormal die life due to the slower heat flow in to the die and therefore lower stress level consequently. From a comparative view of the two alloys, a constant HTC is beneficial in order to obtain a high stress level and therefore a clear result. It should also be mentioned that interface between the die and the molten aluminum will be changed during production cycles. Flaws will occur on the die material but also oxidation layers that will change the HTC.

Simulations of thermal stresses in the die obtained a calculation of die life in a time efficient way, where several casting parameters can be investigated and evaluated. The result showed to be potentially close to reality and therefore those parameters could been estimated through the simulation. The result will be directly influenced of the material data and it must be taken into account that the result will only show a simplified visualization of the reality.

Soldering is a more difficult failure mechanism to evaluate from thermal based criteria. Several factors are contributing to soldering formation, for example chemical composition of the alloy, surface treatment of the die and die spray lubrication. These factors are hard to distinguish from a thermal based simulation however, an increased temperature and time when the die interface is in contact with the molten metal indicates an increased tendency for soldering formation. The critical temperature and time can only be determined by comparison of a foundry experiment. Therefore, it is important to note that the only result of that could be determined by the soldering result is the location, which is most critical for soldering formation.

Mold erosion criteria have been developed in order to determine the locations, which are critical for erosion due to high filling velocity. Several properties besides filling velocity and time are crucial for erosion damage. One is the ability of wear resistance of the die material. When tool steel is exposed of high heat back tempering will occur, which reduces the surface hardness consequently and the wear resistance is reduced. Based on the performance of the die material it is hard to determine the mold erosion. However, since the mold erosion criteria show the location, which is most critical for erosion. The criteria can be valued for location where it is highest risk to get erosion damage, but how big the value will be cannot be stated with high accuracy.

5.2 Discussion of findings

5.2.1 Die life

Die life results showed to be limited due to vital thermal stress amplitude in sharp corners located at the gate area and die cavity. The location of die failure was directly influenced by the casting parameters such as initial temperature, location of tempering channel and

die spray. Stress curves obtained provide input regarding what time the highest stresses were obtained but did not capture the related location and therefore showed which casting step was most crucial.

The results from simulations corresponding to set 1- alloy comparison, are discussed first. The simulation results for die life, based on thermal stresses, showed a clear difference between the two aluminum alloys. The chemical composition had a major effect on the die life prediction. AlSi9MgMn exhibits die life, which is more than twice the amount of cycles as AlMg5Si2Mn before failure when an initial temperature of 640 °C was used. The temperature curves for the two simulations showed that AlMg5Si2Mn had a minimum temperature in the casting below 400 °C and AlSi9MgMn above 400 °C before ejection.

Remarkably however, AlSi9MgMn was held within the phase between liqudius and solidus for a longer time than AlMg5Si2Mn resulting in a slower temperature decrease. This could be attributed to the difference is latent heat of fusion for the alloys which is 411 kJ/kg for AlMg5Si2Mn compared to 461 kJ/kg for AlSi9MgMn. The main reason for this difference can be attributed to the higher silicon content as has been mentioned earlier in the theoretical background section [7].

Comparison of initial melt temperature for simulations of the AlMg5Si2Mn alloy showed that with an increased initial temperature the die life was decreased. The result could be explained in the sense that, with a higher initial temperature the temperature difference between maximum and minimum will be higher resulting in a higher stress amplitude. In Figure 27 and 28, the temperature curve shows that initial temperature had minimal effect on minimal temperature; however, the maximum temperature had a clear impact. According to Rheinfeldens guidelines, the pouring temperature for AlMg5Si2Mn should be 20 °C higher than AlSi9MgMn. Comparison of the two simulations based on their guidelines, die life has been significantly reduced for the AlMg5Si2Mn. Temperature curves for the two alloys see Figure 26 to 28, showed that a higher thermal gradient was observed for the case of AlMg5Si2Mn, which contributed to a shorter die life.

For all three simulations in set 1, the critical areas for failures were in the gate at a sharp corner. Note that these areas are without range of the tempering channels and die spray. The gate is where the molten metal enters the cavity and therefore the location in the die, which is exposed to highest temperature. The stress curves showed that the highest compressive stresses, the highest stress range between tensile and compressive stress were received during filling. It could then be stated that without heat removal the thermal load is hard to counteract, therefore a high stress value will be acquired resulting in die failure. However, whether these results should be considered as thermal fatigue or overheat since no direct cooling have been applied in the area is difficult to establish. It should also be mentioned that evaluation of die life was based on the location in the die where the stress amplitude was highest.

Evaluation of die life restricted to only the cavity and not the gate area showed a different result where the AlSi9MgMn simulation resulted in shortest die life followed by AlMg5Si2Mn (660 °C) and AlMg5Si2Mn (640 °C), see Table 10. This result showed more correlation with the stress curves, where the simulation with highest stress amplitude received shortest die life. As written above, based on the temperature curves, the holding time above solidus temperature for AlSi9MgMn is longer compared to AlMg5Si2Mn. The potential for the alloys to enter solidification is based on how close to eutectic the chemical composition is. Both alloys are hypoeutectic forming α-Al dendrites in a first phase eutectic. If the solidification rate is slow, heat extraction rate can correspondingly be lower.

This results in a longer heat exchange between the interfaces, which prolongs the thermal load and subsequently increases the stress range.

The results from simulations corresponding to set 2- process parameters are discussed next. All three simulations for process parameters were performed for AlSi9MgMn with an initial temperature of 640 °C. The results showed that simulation performed only with die tempering from tempering channels exhibited shortest die life followed by simulation where only die spray was included. It is remarkable that the simulation performed with no cooling showed more than twice as long die life as the other two simulations. Based on the temperature curves, see Figures 29 to 31, it is perceived that the simulation performed only with die tempering channels had gotten a more rapid temperature decrease and lower minimum temperature. It is important to note that the crack location for the simulation performed only with die tempering channels were at the gate and at sharp corners within the die cavity for the other two simulations.

If the gate area was not taken into the evaluation, the result would be different with a much longer die life ~600 000 cycles in the die cavity for the simulation performed with only tempering channels. The simulation performed with only die spray would then get the shortest die life. The reason for this result is that tensile stresses caused by die spraying are most detrimental to die life and the resulting stress levels are based on how effectively the temperature decreases before die spraying is applied.

5.2.2 Soldering and Erosion

Since soldering results are based on the time that the die interfaces are above a temperature of 558 °C, it can be directly attributed to the temperature curves, see Figure 26 to 31. The only critical locations for soldering formation were at the edge of the gate for all simulations. In this location, die tempering channels and die spray are outside the range, which makes it more prone for higher temperature than the rest of the die.

Soldering results for the alloy comparison simulations showed that AlSi9MgMn had a higher soldering tendency compared to AlMg5Si2Mn with an initial temperature of 660 °C. The temperature curves support the results of soldering formation based on longer holding time above the critical temperature. It is important to note that MAGMAsoft only uses thermal-based criteria of temperature and holding time for this evaluation. If a physical test would be conducted, the results would most likely look different since other corresponding phenomenon, which influence the chemical interaction between Fe and Al alloys such as diffusion, would also play a significant role.

The results for the soldering from set 2 i.e., the process simulation showed a similar result where the simulation that had been above the critical temperature for the longest time was most prone to soldering formation. The simulation performed with no cooling had also the slowest rate of temperature decrease and therefore most critical for soldering formation.

The results concerning erosion from set 1 and set 2 of simulations are discussed next. The critical locations for mold erosion for all simulations were at the ribs in the die cavity. Mold erosion is characterized by the criterion of filling velocity and time where this velocity exceeds 60 m/s. The critical location for mold erosion could be found in the cavity ribs. The metal flow causing erosion could clearly be traced from the gate area to the ribs where the wall thickness becomes thinner resulting in locally increased velocity. For alloy comparison, the result showed that AlMg5Si2Mn with an initial temperature of 640 °C was

most prone to erosion formation on the die. Comparison of process parameters showed that the simulation performed only with die spray obtained the highest amount of mold erosion. It should be mentioned that the mold erosion value for all simulations was low. While it is difficult to quantify the difference in erosion results within each set and between the two sets, the location where the highest risk for erosion damage exists based on design can clearly be evaluated.

5.3 Research questions summary

- **What failure mechanisms determine the die life in HPDC?**

Three main failure mechanism have been taken into account through the simulations, thermal fatigue, soldering and erosion. However only thermal fatigue could determine die life. Chemical composition showed to have a major influence on die life, based on thermal stresses. It was noted that solidification time played an important role in the time of heat contact between the interfaces. The ability of solidification is based on how close to eutectic the chemical composition is. A slower solidification results in a longer heat contact between the interfaces, which increases the stress range and reduces die life.

Based on the literature review, it was also clear that the die is exposed to a higher risk for soldering formation, depending on the time when the interface is above a critical temperature. The heat released during solidification, which was higher for alloy with higher silicon content, decreased die life. The gate area is the location of casting that is exposed to heat for the longest time and are therefore most prone of failure based on thermal stress. It can be mentioned that design of the die can play an important role in the failure mechanisms but was not studied in this thesis.

- **What is the influence on die life from processing variables such as**:
    - How will casting cycle performed with no cooling resulting in superheat influence the die life?
    - What influence will time specified die spray have on the die life without internal cooling?
    - How will constant cooling from tempering channels influence the die life during the casting cycle?

Tempering channels were the most effective process parameter due to efficiency of heat removal. Optimization of both tempering channels and die spray prolong a suitable die life. However, die spray performed without the usage of tempering channels showed to be critical for die life since it promoted a higher stress range. The most critical location of failure was in the gate, an area not exposed to effective heat removal of tempering channels or die spray resulting in superheat. Here a high initial temperature could enhance the risk for superheat resulting in short die life.

5.4 Conclusions

- Calculations of die life based on thermal stress showed that the alloy AlMg5Si2Mn was most prone to failure in the gate area due to a higher thermal load. However, in the cavity where tempering channels and spraying were applied, lowest die life was observed for AlSi9MgMn. The most crucial process parameter to achieve longer die life was the tempering channels, which contribute to effective heat removal.

- Tempering channels and die spray prevents the die from being exposed to temperatures above the critical temperature defined for soldering formation.
- Mold erosion formation occurred consistently in the same location. This suggests that die design optimization is crucial to minimize the local filing velocity increase in the die.

Recommendations for further work

For future work, it would be of interest to validate the findings in this report generated through simulations with a real industrial test. This would provide a more comprehensive picture of the failure mechanisms in dies for HPDC and the numerical influence of the simulation. Regarding numerical influence of the results, it would be interesting to run simulation with finer mesh in order to validate any change of results.

It would also be of interest to simulate a more complex design and see if the result still is valid or if it changes based on design. Design experiments could be done with variation of casting thickness, radius sharpness and filling design. Another work could extend the simulations to other alloying systems for both aluminum and tool steel materials.

To perform simulations with more correct properties of the die material, one critical parameter is the selection of fatigue data for the Wöhler curve. It needs to be further investigated if the selection of fatigue data with tests performed at a constant elevated temperature is appropriate for evaluation of die life based on thermal fatigue. Research of available technology with possibility to measure stress based on thermal load with credible temperature variation from a HPDC perspective. That could result in a Wöhler curve close to an exact material property for the application.

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