TAMPERE UNIVERSITY OF TECHNOLOGY

TONI SIIK

THE VERIFICATION OF LOW-PRESSURE DIE CASTING SIMULATION RESULTS

Master's Thesis

Examiner: Professor Tuomo Tiainen

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ABSTRACT

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In this thesis the accuracy of low-pressure die casting simulation results is both verified and improved for the casting process at Oras Oyj. The accuracy of casting simulation depends on the correctness of the initial data used for the simulation. This data include the process parameters and material data. As casting simulation programs only usually provide a limited database for the materials available on purchase it is often necessary to expand this database by modeling more materials and providing the correct process parameters of the simulated process.

The main goal of this project was to verify the correctness of the most important process parameters, material data and the actual results. With correct values the simulations can provide valuable information to the product designers and production. This information can be used to design better products and molds from the concept stage forwards. The simulation results can be used to improve old products.

The project was divided into two separate parts, theoretical and experimental sections. The theoretical section of the project concentrated on providing background information on the data which needed to be verified.

During the experimental section of the project, data was acquired which could be used to tune the simulation program. The data on casting alloys were improved by simulating the materials properties which were needed. These simulated properties were verified by using the thermal analysis of the casting alloys. The mold materials were

tested at Jönköping University for the needed properties. All of these measurements were used to model the casting alloys and mold materials into the simulation programs database.

An experimental mold was also manufactured; this mold was used to measure the temperature-time curves inside the mold material during the casting cycles. The mold was used to cast test-castings of each different casting alloy which had to be simulated. The thermal data acquired from these test castings was compared to the simulated thermal data and the simulation program was adjusted until the results were comparable.

The accuracy of the simulation results was increased significantly due to the improved data acquired during this project. After this project simulation can be used as a tool in tool design and in finding the sources of quality problems. The data can still be improved by comparing the simulation results of more cases to the results obtained from real castings.

TIIVISTELMÄ

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Tässä diplomityössä sekä varmennettiin että parannettiin Oras Oyj:n matalapainevalu-prosessin simulointitulosten tarkkuutta. Simulointien tarkkuus riippuu pitkälti simulointiohjelmistoon syötettävien alkutietojen tarkkuudesta. Nämä tiedot sisältävät sekä prosessiparametrit että materiaalidatan. Useimmissa tapauksissa valunsimulointiohjelmistot sisältävät suoraan jonkin laajuisen materiaali- ja prosessiparametri-tietokannan, mutta usein tätä tietokantaa on laajennettava mallintamalla sinne uusia materiaaleja ja lisäämällä todellisen prosessin prosessiparametreja.

Tämän projektin pää-tavoitteena on ollut varmentaa Oras Oyj:n valuprosessin tärkeimmät parametrit, käytetty materiaalidata sekä tulokset. Oikein kalibroituna valunsimulointia voidaan käyttää työkaluna valujensuunnittelussa ja tuotannossa. Simuloinneista saatavaa tietoa voidaan käyttää hyväksi paremmin valmistettavien tuotteiden suunnittelussa aina konsepti-tasolta lähtien. Vaihtoehtoisesti simulointituloksia voidaan käyttää vanhojen tuotteiden valmistettavuuden parantamiseksi.

Tämä projekti voidaan jakaa kahteen eri osaan, teoreettiseen osaan ja käytännön osaan. Teoreettisessa osassa pyrittiin keräämään taustatietoa varmennettavista tiedoista.

Kokeellisessa osassa hankittiin ja mitattiin tarvittavaa tietoa simulointiohjelmiston hienosäätöä varten. Valettavien seosten ominaisuuksia ja tietoja parannettiin

simuloimalla materiaaleja niiden ominaisuuksien tarkentamiseksi. Nämä simuloidut tulokset varmennettiin termisen analyysin keinoin. Muottimateriaalit testattiin Jönköpingin Yliopistossa. Kaikki hankittu tieto käytettiin ohjelmiston tietokannan päivittämiseen.

Projektia varten valmistettiin myös instrumentoitu koemuotti, jonka avulla pystyttiin mittaamaan lämpötiloja muottilaattojen sisältä valusyklien aikana. Simulointiohjelmistoa hienosäädettiin tämän jälkeen kunnes simuloidut tulokset saatiin vastaamaan mitattua lämpötilatietoa.

Simulointitulosten tarkkuus parani projektin johdosta huomattavasti. Projektin ansiosta simulointia voidaan käyttää paremmin työkaluna niin tuotteiden kuin työkalujenkin suunnittelussa sekä valuongelmien ratkaisussa Oras Oyj:n prosessissa. Tuloksia voidaan jatkossa parantaa tarkentamalla edelleen ohjelmiston parametreja. Tämä voidaan tehdä vertaamalla simulointituloksia valettuihin kappaleisiin.

PREFACE

First of all, I want to thank everybody at Oras Oyj. for providing this interesting project for me to work on and for all of their support. I am also very grateful for the guidance, knowledge and feedback I have received from Professor Tuomo Tiainen during this project. I would not even have become interested in this field of studies without the interesting courses held by Tuomo.

Most of all I would like to thank my family and friends for their support and encouragement received during this project. Without you I would not be here today.

Tampere 2011

TONI SIIK

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ABBREVIATIONS AND NOTATIONS

LPDC - Low-pressure die casting

HTC - Heat transfer coefficient

FEM - Finite element method

FVM - Finite volume method

MAGMASOFT - A casting simulation software suite

ASM - American Society of Metals

UNS - Unified numbering system to identify different alloys

DSC - Differential Scanning Calorimetry

1 INTRODUCTION

This Master of Science thesis was a part of a Tekes-funded project, which was aiming to implement the use of casting simulation in the production of yellow brass castings at Oras Oyj. The main goal of the thesis was to verify the simulation results obtained with the software and to take the necessary steps to improve the accuracy of the simulation results.

Casting simulation is an FVM-based technique which can be used to simulate and forecast the filling of the mold, solidification and properties of castings. Casting simulations have become more common as the calculation times for the simulations have decreased with the increased computational power of workstations and clusters. The decreased calculation times for the simulations have made it possible to increase the accuracy of the simulations so that even smaller details of the casting process can be simulated. The increased accuracy of simulation results can be used to improve the casting design, improve the yields of castings, and to improve the casting quality. When all of these are achieved, significant savings can be expected.

While casting simulation programs usually include some process data database, at least some of the parameters and values of the casting processes are individual in each foundry. In addition foundries often use in their process materials which are not included in the database which leads to the need to describe those materials into the programs database. While most values and parameters in the casting process can be approximated, either by mathematical models and approximations, measuring the actual process parameters and values usually provides much better results.

The experimental part of the thesis included the description of two casting alloys and two mold materials into MAGMASOFT. The casting alloy models developed for the database were based on mathematical models of the alloys, which were calculated for the two alloy compositions used at the foundry. These mathematical models were verified by thermal analysis. The two mold materials were described using the results of actual measurements performed on actual samples of each material.

An instrumented test mold was produced for the project with the goal of providing measurement data which could be used to determine the heat transfer coefficients (HTCs) for the several different material interfaces existing in the system.

The data acquired from the test mold was used to fine-tune the HTC-values within the simulation program so that the simulated data from the software was as close as possible to the data measured from the test-mold.

The results of this thesis were used to fine-tune the simulation program at the client for their process so that it would provide them with accurate simulation results. This could be used as a good tool in helping design decisions and to fine-tune the casting systems.

THEORETICAL BACKGROUND

2 LOW-PRESSURE DIE CASTING (LPDC)

Low-pressure die casting is one of the permanent mold castings techniques, which has been used since the 1950s. It is commonly used as a production technique for high-volume, high-quality and high-integrity components from nonferrous metals such as aluminum, magnesium and many copper base alloys. Aluminum is the most used alloy with the LPDC-technique. With aluminum some of the most common applications are critical components for the automotive industry, such as engine blocks, wheels and suspension components. The casting weight is usually between 5 kg and 100 kg, but both smaller and larger castings are possible. When casting copper base alloys such as brass, one of the most common applications are plumbing components, such as valves, faucets and water meter bodies. (Bader 2002) (Woycik and Peters 2008)

2.1 Advantages of the process

The casting technique is well suited to many components with large- to medium-size series where casting quality is important. One of the main advantages of the process is the highly controllable filling of the mold cavities, which in turn makes the filling of the mold as non-turbulent and as smooth as possible.

This results in usually 5-6% better mechanical properties when compared with similar castings produced with gravity casting techniques from the same alloys. One of the reasons for the improved mechanical properties is the lack of entrained oxide films, which is resulting from the smooth filling of the cavities. The presence of the oxide films is further reduced by the fact that the melt which is forced into the mold is taken inside the melt in the furnace. This eliminates the oxide films which are most commonly found on the melt surface at the upper part of the furnace. The highly-controlled filling also results in a very low rejection rate.

Another significant advantage of the process is that the riser volume of the castings can be minimized with correct casting design. When casting systems are designed so that the final solidification of the casting moves from the top of the product to the gating system, it may be possible to leave out risers completely. The lack of risers will improve the yield of the castings significantly and it will also lower the manufacturing costs of the castings as less work will be required for the cleaning of the castings.

The reason why low-pressure die casting is one of the best casting techniques for casting brass plumbing components, such as faucets and valves, is that the technique allows for complex external and internal shapes. They are possible to obtain with the use of sand cores. As a large portion of brass castings will end up with finishing by grinding, polishing and chromium plating, low-pressure die casting also provides the high casting quality which is needed for these components. Due to the long production process the faults which are found in the last stages of manufacturing, become very expensive. With correct mold design and good process control, the faults which originate in the casting stage can be minimized. (Bader 2002) (Woycik and Peters 2008) (Campbell 2003)

2.2 The process

Low-pressure die casting machines are highly automated and usually require only one operator for each machine. The operator takes care of starting the casting cycle, of inspecting the castings, and of inserting the necessary cores. Depending on the mold structure, the operator may also be responsible for removing the castings from the molds. Ideally the process parameters should be established well before the molds are used in production, but often the operators are also responsible for adjusting the process parameters when necessary.

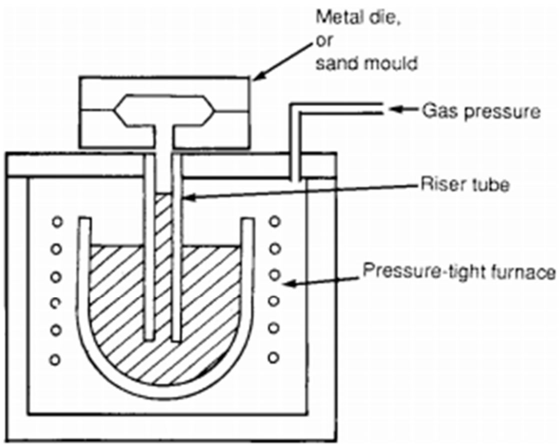

Figure 1 - The basic structure of a LPDC-machine. (Campbell 2003)

The LPDC machines most often have a general structure which can be seen in Figure 1. The machines consist of the mold structure and a hermetically sealed furnace. Depending on the casting machine the mold can have either a vertical or a horizontal parting line. The basic working principle of both machine types is similar, but the mold structure is different. The machine shown in Figure 1 has a horizontal parting line which enables the lower half of the mold to be stationary on the top of the furnace, with the upper mold half moving with the moving platen. The machines with a vertical parting line usually have both sides of the mold moving with a manipulator. The both casting machines which were used during the thesis work had vertical parting lines as the vertical parting line is better suited for the type of castings that the Oras produces.

With the vertical parting line, the mold is moved between two different positions, the furnace and a preparation station. At the preparation station, the mold is prepared by dipping the mold halves in graphite water to control the temperature of the mold and to add a graphite layer on the mold cavity. After dipping the mold, cores are added and the mold is closed. After this the mold is moved to the furnace for filling. When the mold is securely positioned on top of the furnace nozzle, the casting machine starts adding pressure to the sealed furnace so that the molten metal is forced up the riser tube and into the mold. The riser tube extends deep below the surface of the molten metal, ensuring that the metal filling the mold is free of excessive oxide films and inclusions. The casting machine adjusts the pressure within the furnace enclosure according to a predetermined pressure curve. After the mold has finished filling, the pressure is retained for a needed amount of time so that the metal has enough time to solidify within the mold. The required holding time for the pressure is different for each mold. Optimally the pressure is held until the casting is solidified up to the furnace nozzle. This way the minimum amount of cold metal is returned to the furnace when the pressure is dropped. After the pressure is removed from the furnace interior, the mold is moved back to the preparation station, where the mold is opened and the casting is removed either by ejection pins or by the operator of the machine. After the casting has been removed and the mold cleaned, the cycle can start from the beginning. A basic production line diagram for low-pressure castings is presented in Figure 2.

With horizontally parted molds, the cycle is more or less the same. The biggest difference is that the mold pieces are not dipped for temperature control, but the required heating and cooling channels have been integrated into the mold. Then the mold temperatures can be controlled with more precision. For example, it is possible to start the cooling of the mold in certain areas even during the casting cycle. The casting machines with horizontal molds are by far more likely to be controlled with the help of thermocouples located inside the mold structures. The reason for this is that the instrumentation is easier to build with a mold structure which does not move. Often the instrumentation can be built adjacent to the tempering channels of the mold. (Bader 2002) (Woycik and Peters 2008) (Campbell 2003)

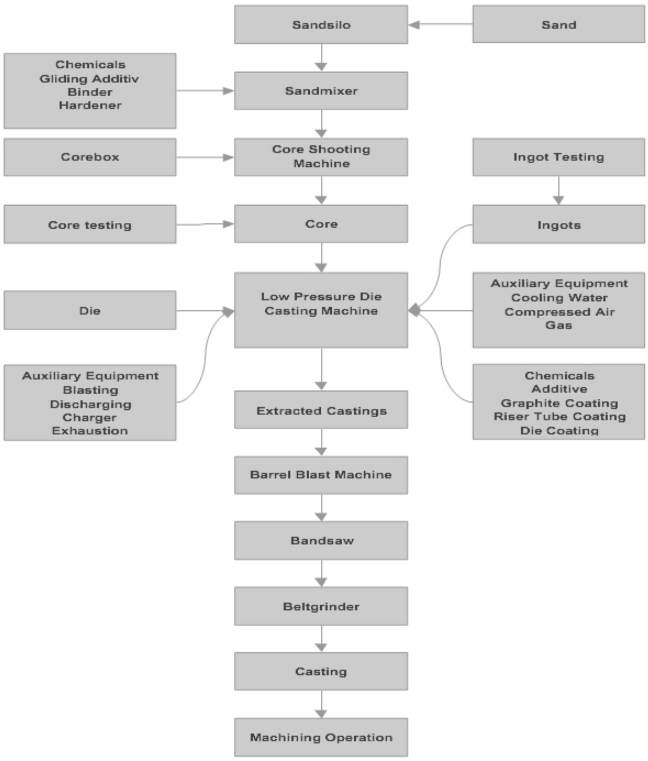

Figure 2 - Low pressure die casting production line. (Bader 2002)

2.3 Future development

While low-pressure die casting is one of the most reliable casting techniques for high quality parts there are several areas with room for improvement. One of the main areas where the improvements are significant issues is the insufficient melt velocity control. Often filling rates are increased to improve the cycle times. While the higher filling rates may lower the cycle time, the benefits are outweighed by the problems this causes.

There are some visions how this issue can be solved. The computerized control of the casting machines often makes it possible to use optimized pressure curves for filling. When the pressure curves are optimized correctly, filling speeds are optimal at each point of filling. The optimized filling curves are still not common as this optimization is not easy. It is challenging to determine the actual rate by which the mold is filled without the use of instrumented molds. This causes the optimized pressure curves often to get out of phase, causing even more problems than the non-optimized pressure curves.

In the future we may see more molds, where it is possible to determine the rate of filling in real-time through the use of probes. John Campbell suggests that this could be carried out by monitoring the pressures of the inert gases above the mold and by measuring the changing capacitance between the melt and mold clamp plate. (Campbell 2003)

Another possible area of improvement in low-pressure die casting is the die coatings. When casting copper base alloys with low-pressure die casting the molds are traditionally coated with graphite. Now new coatings are becoming available which improve the control over the heat transfer from the melt to the mold. Better coating materials will improve both the quality of the castings and the control of the casting process.

3 CASTING AND MOLD MATERIALS

3.1 Copper alloys

Copper alloys can be divided into six different groups by their composition. The groups include coppers, high-copper alloys, brasses, bronzes, copper nickels and nickel silvers. The coppers contain less than 0.7% of other elements than copper while the high-copper alloys can contain up to 8% of alloying elements. The main alloying elements and their contents in the other copper alloy groups can be seen in Table 1.

Table 1 - Different copper base alloy groups and their main alloying elements. (Sadayappan, Sahoo and Michels 2008)

Family	Alloying elements	Solid solubility, at.%(a)
Brasses	Zinc	37
Phosphor bronzes	Tin	9
Aluminum bronzes	Aluminum	19
Silicon bronzes	Silicon	8
Copper-nickels, nickel silvers	Nickel	100

All of the different copper alloys are considered as castable, but the castable alloys have different standards which allow for different compositions than the wrought alloys. Most of the compositional differences are due to efforts to improve the castability of the alloys. The more accurate division of the alloys can be seen in Table 2.

Table 2 - Copper base alloys and their UNS-standard numbers. (Sadayappan, Sahoo and Michels 2008)

Generic name	UNS numbers	Composition
Wrought alloys		
Coppers	C10100-C15760	>99% Cu
High-copper alloys	C16200-C19600	>96% Cu
Brasses	C20500-C28580	Cu-Zn
Leaded brasses	C31200-C3890	Cu-Zn-Pb
Tin brasses	C40400-C49080	Cu-Zn-Sn-Pb
Phosphor bronzes	C50100-C52400	Cu-Sn-P
Leaded phosphor bronzes	C53200-C54800	Cu-Sn-Pb-P
Copper-phosphorus and copper-silver-phosphorus alloys	C55180-C55284	Cu-P-Ag
Aluminum bronzes	C60600-C64400	Cu-Al-Ni-Fe-Si-Sn
Silicon bronzes	C64700-C66100	Cu-Si-Sn
Other copper-zinc alloys	C66400-C69900	...
Copper-nickels	C7000-C79900	Cu-Ni-Fe
Nickel silvers	C73200-C79900	Cu-Ni-Zn
Cast alloys		
Coppers	C80100-C81100	>99% Cu
High-copper alloys	C81300-C82800	>94 Cu
Red and leaded red brasses	C83300-C85800	Cu-Zn-Sn-Pb (75–89% Cu)
Yellow and leaded yellow brasses	C85200-C85800	Cu-Zn-Sn-Pb (57–74% Cu)
Manganese bronzes and leaded manganese bronzes	C86100-C86800	Cu-Zn-Mn-Fe-Pb
Silicon bronzes, silicon brasses	C87300-C87900	Cu-Zn-Si
Tin bronzes and leaded tin bronzes	C90200-C94500	Cu-Sn-Zn-Pb
Nickel-tin bronzes	C94700-C94900	Cu-Ni-Sn-Zn-Pb
Aluminum bronzes	C95200-C95810	Cu-Al-Fe-Ni
Copper-nickels	C96200-C96800	Cu-Ni-Fe
Nickel silvers	C97300-C97800	Cu-Ni-Zn-Pb-Sn
Leaded coppers	C98200-C98800	Cu-Pb
Miscellaneous alloys	C99300-C99750	...

3.1.1 Castability of copper base alloys

Castability is a term which tries to establish how easy the alloys are to use in casting processes. For an alloy to be considered as castable it must be relatively easy to produce sound castings with that alloy. All copper alloys can be cast using sand casting technique, but only some of the alloys are commonly used in die casting. Pressurized die casting is mainly used to cast different yellow brass grades, for which the technique is well suited. The castability ratings (according to ASM) of some of the casting alloys can be found in Table 3.

Table 3 - Castability rating of copper alloys according to ASM. The ratings go from 1 to 8 with 1 being the best rating and 8 the worst. (Sadayappan, Sahoo and Michels 2008)

UNS number	Common name	Shrinkage allowance, %	Approximate liquidus temperature		Castability rating(a)	Fluidity rating(a)
			°C	°F		
C83600	Leaded red brass	5.7	1010	1850	2	6
C84400	Leaded semired brass	2	980	1795	2	6
C84800	Leaded semired brass	1.4	955	1750	2	6
C85400	Leaded yellow brass	1.5–1.8	940	1725	4	3
C85800	Yellow brass	2	925	1700	4	3
C86300	Manganese bronze	2.3	920	1690	5	2
C86500	Manganese bronze	1.9	880	1615	4	2
C87200	Silicon bronze	1.8–2.0	...	...	5	3
C87500	Silicon brass	1.9	915	1680	4	1
C90300	Tin bronze	1.5–1.8	980	1795	3	6
C92200	Leaded tin bronze	1.5	990	1810	3	6
C93700	High-lead tin bronze	2	930	1705	2	6
C94300	High-lead in bronze	1.5	925	1700	6	7
C95300	Aluminum bronze	1.6	1045	1910	8	3
C95800	Aluminum bronze	1.6	1060	1940	8	3
C97600	Nickel-silver	2	1145	2090	8	7
C97800	Nickel-silver	1.6	1180	2160	8	7

3.1.2 Main alloying elements in copper alloys

Zinc

Zinc is the most used alloying element in copper alloys due its low price and solid-solution strengthening properties. It both lowers the alloy price and adds strength and hardness at the same time. Contents up to 36 wt.-% can be used to produce alloys which have a single-phase structure which is called alpha brass. When the zinc content is higher, the structure of the alloy turns to alpha-beta brass.

Tin

Tin is the oldest alloying element found in copper base alloys. It has by far higher strengthening effect on the alloys when compared to zinc. It also improves the corrosion-resistance and enhances the castability by increasing the fluidity and solidification range of the alloys. Tin is used in copper alloys up to the content of 11.5 wt.-%.

Lead

Lead is a common alloying element found in many copper alloys even though it is insoluble in copper. The lead found in these alloys forms a separate phase which solidifies last. Due to this behavior it is found in the grain boundaries and interdendritic areas.

Lead is used in the alloys for many different reasons. It has been found to improve the soundness of castings for example by filling the pores which form during solidification. This makes it easier to produce pressure-tight castings. High-lead alloys are also used in bearings, where the added lead improves the tribological aspects of the alloys. In the bearings the lead acts as a dry lubricant. Machinability is also improved with the addition of lead as the lead phases work as natural chip breakers.

Aluminum

Aluminum is used in copper alloys with contents up to 9 wt.-%. Aluminum strengthens the alloys by solid solution strengthening and therefore it is used in the high-strength alloys. When aluminum is added in small amounts, it also improves the melt fluidity of some of the copper alloys such as the yellow and silicon brasses.

Silicon

Silicon containing alloys are commonly used in art castings as the silicon increases the melt fluidity of the alloys. Contents of up to 5 wt.-% are used.

Nickel

Nickel is found in the copper-nickel alloys which exhibit high resistance to corrosion. The copper-nickel alloys are commonly used in the petroleum, chemical, food and dairy industries. Nickel additions in copper alloys also improve the strength and creep resistance. Nickel is also slightly better in improving the pressure tightness of castings than lead when used in bronze and semi-red brass alloys.

Beryllium

Beryllium strengthens the copper alloys by providing an interdendritic precipitate. The increased strength comes with a loss in electrical and thermal conductivity and the ductility of the alloys. Typically the electrical conductivity of commercial Cu-Be alloys is of the order of 15-20% IACS, where 100% IACS represents the electrical conductivity of 100% pure copper.

Chromium

Chromium is used as a strengthening agent in the alloys. Chromium additions lower the thermal and electrical conductivities only slightly when compared with pure copper alloys.

Iron

Iron is one of the nonsoluble alloying elements used in copper alloys. Its exact influencing mechanism is not well known, but iron is used as a grain refiner in brasses and aluminum bronzes. Iron increases the melting temperature of the alloys and the tendency of hard spot formation. It also increases the strength of the alloys. If magnetic susceptibility has to be considered the iron content should be less than 0.01 wt.-%.

Antimony

Antimony is used in small amounts in brasses to encounter then dezincification process where the zinc evaporates from the molten alloys. When present in tin bronzes, it reduces the strength and ductility.

Bismuth

Bismuth is considered to be an impurity in the high-strength alloys where only 0.01 wt.-% of bismuth can cause embrittlement. It is also used to replace lead in some of the brass alloys where it improves the machinability and pressure tightness of the alloys. Bismuth is used to replace the lead in the alloys as it is less hazardous to the health when compared to lead.

3.2 Casting alloys – Brass alloys

Brasses are one group of the many different copper base alloys. All brass alloys have zinc as their main alloying element. In addition to zinc the brasses may contain tin, lead, iron, aluminum, nickel, silicon and bismuth. The brasses are divided into many different categories depending on their composition. (Sadayappan, Sahoo and Michels 2008)

As all brasses have zinc as the main alloying element the phase diagram in Figure 3 shows the main phases which can be found in brasses. The alloys whose behavior is studied in this thesis are located between 35 and 40 wt.-% contents of zinc. As evident from the diagram, the solidification of the alloy starts at higher temperatures with the formation of the alpha phase. After the peritectic solidification temperature has been reached the beta phase will form together with the alpha phase. With the alloys in question the end phase for the brass will stay within the alpha area. The beta phase will change back to the alpha phase as the temperature of the alloy drops below the transition temperature. This transition temperature depends on the composition of the alloy and it can be used to determine the composition of the alloy.

The alloy compositions which were studied in this thesis have the effective copper value of 61.5% which translates into ~38.5 % zinc, causing the end structure of the alloy to become alpha-beta. The dezincification of this alloy can be controlled by the addition of inhibitors and by controlling the grain size. (Sadayappan, Sahoo and Michels 2008).

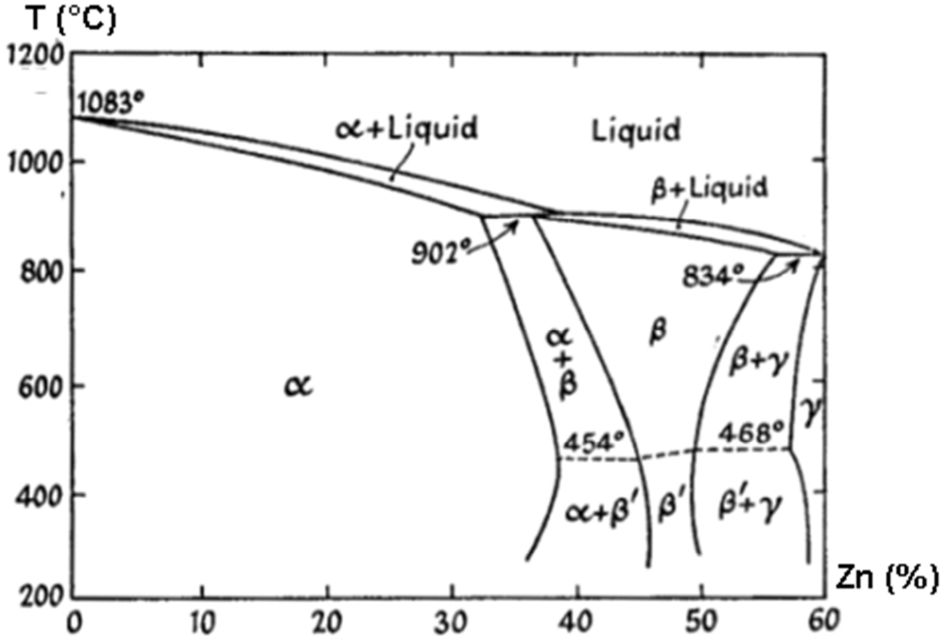

Figure 3 - Phase diagram of the Cu-Zn-system. (Key To Metals AG 2010)

3.2.1 Yellow brass (CuZn36Pb1)

The CuZn36Pb1 alloy grade is used in the vast majority of Oras products. It is a traditional yellow brass which has a 1 wt.-% content of lead to improve the casting properties of the alloy and to improve the pressure-tightness of the castings. The grade is fairly easy to cast and the machinability of the alloy is good due to the lead content.

3.2.2 Low lead yellow brass

Low-lead yellow brasses are making their way into the foundries due to the need to decrease or to remove completely the lead from the alloys in products which come into contact with potable water. Even though the amounts of lead used in the current CuZn36Pb1 alloys are small, there is a concern that even those amounts of lead may dissolve into the water causing health problems as the lead accumulates in the human body over time. The drive to lower the lead-content in these products originates in the United States. While there are currently no major restrictions on lead-content in Europe it has become a topic of discussions in many countries.

The low-lead alloys have different properties when compared with the currently used alloys. The liquidus and solidus temperatures of the most low-lead alloys are higher than those of the conventional lead containing alloys. Due to the higher melting and solidification temperatures, the casting temperature control becomes even more crucial. The lack of lead also seems to cause a need for a higher degree of feeding of the alloys, which can be seen as bigger feeding pores in the cast components. The lack of lead also makes it harder to produce pressure-tight castings as there is no phase which would fill in the pores which are formed when the alloy solidifies. The higher solidus and liquidus temperatures also often cause the low-lead alloys to solidify too early during the casting cycle. This behavior leads to filling and quality problems.

The machinability of the low-lead yellow brasses is often also worse than that of the leaded alloys. This is caused by the lack of chip breaking inclusions and dry lubricant within the alloy structure.

3.2.3 Other nonleaded yellow brasses

There are many alloys currently available to the industry where the lead in the brasses has been replaced with other alloying elements. As mentioned earlier, bismuth has been used to replace the lead in the casting alloys for health and environmental reasons. While bismuth still has toxic properties (Figure 4), they are less significant and bismuth does not accumulate in the human body. This makes it safer for use in plumbing applications where there is a possibility that some of the alloying elements are dissolved in the water over long periods of time.

The addition of bismuth to the alloys may cause embrittlement due to its tendency to accumulate at grain boundaries. This tendency can be avoided if the zinc-concentrations of the alloys are sufficiently high. (La Fontaine and Keast 2006)

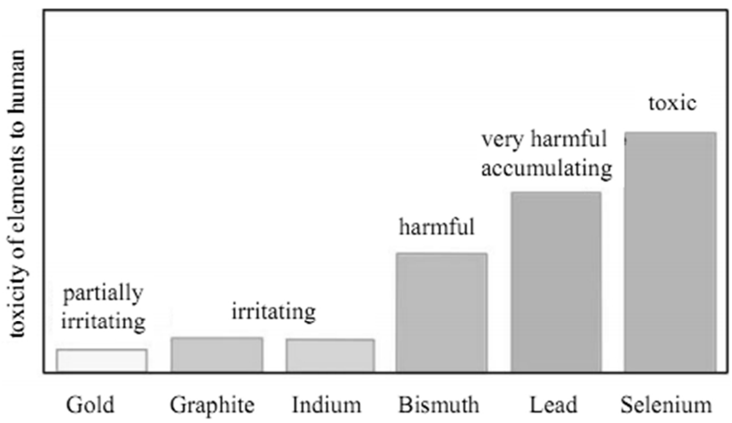

Figure 4 - The toxicity of several different elements. (Kondracki and Szajnar 2007)

3.3 Mold materials in low pressure die casting

As the vast majority of low-pressure die casting components are produced from aluminum the most common mold materials are different tool steels. While steel may be the optimal material for aluminum casting, in copper alloy casting the temperatures are too high for the steel molds. The steel molds wear down too fast.

Carbon steel molds are suitable for copper alloy castings only when the annual casting volumes are low enough. The approximate expected lifetime of a carbon steel mold is only about 5000 castings according to one of the casting machine manufacturers. The main reason for the short lifetimes of carbon steel based molds, when used to cast copper base alloys, is caused by the materials lower thermal conductivity. The lower thermal conductivity of the material causes larger temperature differences within the mold, causing tearing in the molds. The wear properties of the carbon steel molds would be much better than those of copper alloy molds. (Bader 2002)

Copper alloy based molds are by far more suitable for casting copper alloys, as they last much longer. The most common mold material when casting copper alloys is beryllium copper, which usually provides a lifetime of 50 000 castings. In addition the copper base alloy molds can be reworked several times, providing even an even better lifetime with minimal added costs. Often the copper molds also produce better quality castings, which is crucial when producing consumer products where the surfaces of the castings will often, are polished and electrically coated with chrome. The influence of the mold material should however not be the determining factor in the quality of castings as good casting quality should come from good casting design. (Bader 2002)

3.3.1 CuCrZr – alloys

CuCrZr-alloys are precipitation hardenable high-copper alloys where the hardness, thermal and electrical conductivities are still at a high level. This set of properties makes the material ideal for applications where high strength and excellent thermal and electrical conductivities are required. The most common applications of the material include welding tips and electrodes for spot welding and spark erosion and parts in electrical equipment which are subjected to high stresses, but still require high electrical conductivity. (Metaal n.d.)

The alloying elements present in the CuCrZr-alloys are chromium and zirconium. Chromium is added to the alloy to improve the strength of the alloy while lowering the electrical and thermal conductivities only slightly. Zirconium is added to the alloys to provide strength through precipitation hardening. (Sadayappan, Sahoo and Michels 2008) (MatWeb n.d.)

When comparing the CuCrZr-alloys to the beryllium copper alloys, they offer better electrical and thermal conductivity, but have smaller strength and hardness. The improved thermal conductivity can also be seen as a disadvantage of the material when used as a mold material. When the material has higher thermal conductivity, it removes heat from the molten metal faster, making the castings to solidify faster. This makes it harder to fill the molds as the melt often cools down too fast. The heat transfer from the molten metal to the mold can be adjusted by using die coatings which lower the heat transfer between the mold and molten metal.

The higher thermal conductivity of this material can also cause hot-tearing in the brass castings. While the exact reason for this behavior is not known, it is suspected that it may be caused by the steep temperature gradients in the casting while it is solidifying. This tendency can be decreased by using die coatings which lower the heat transfer from the melt to the mold.

The CuCrZr-alloys are used at Oras due to the health risks adjacent to the use of beryllium copper alloys.

3.3.2 Beryllium copper alloys

Beryllium copper alloys belong to the high-copper alloys as the alloying elements only account up to 3% of the content. While the beryllium coppers can be produced with various different manufacturing methods, the wrought alloys are most commonly used as mold materials. The phase diagram for the copper-beryllium-system is shown in Figure 5.

The addition of beryllium in copper has a big influence on the properties of the resulting alloys. When alloyed with copper, it promotes significant precipitation hardening, while keeping the thermal conductivity at reasonable levels. The improved properties of the alloys make them highly usable in electrical components, control bearings, housings for magnetic sensing devices and in resistance welding. (Harkness, Spiegelberg and Cribb 1990)

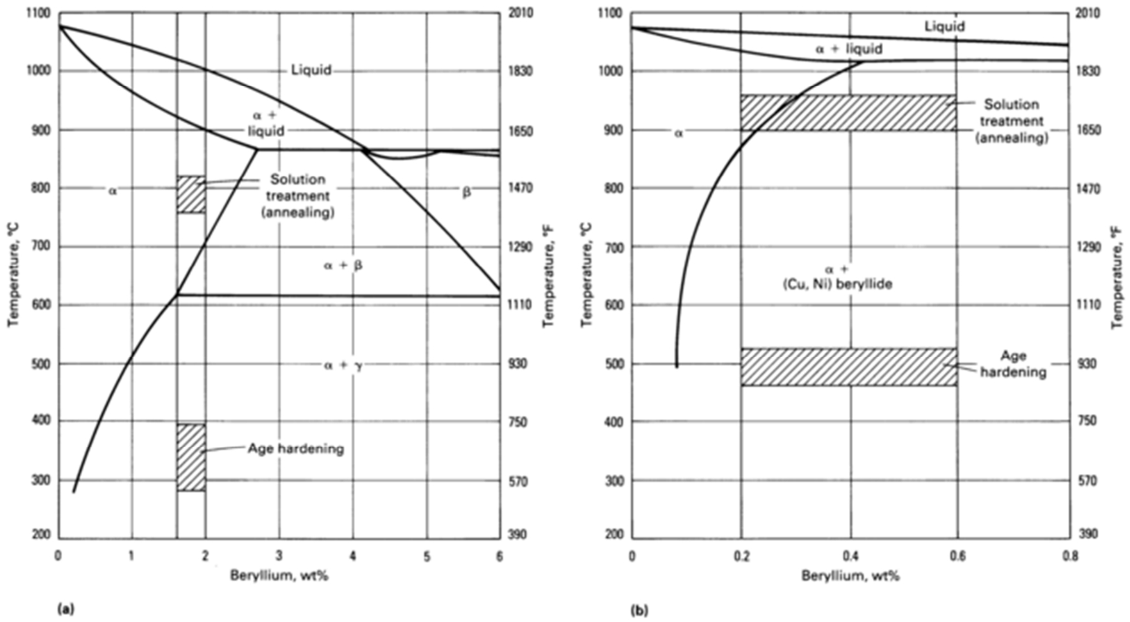

Figure 5 - Phase diagrams of the Cu-Be-system. (Harkness, Spiegelberg and Cribb 1990)

Beryllium coppers are used as mold materials when casting copper base alloys due to the improved strength of the alloy. An additional useful property is the lowered thermal conductivity of the alloys as this helps the filling of the molds properly during casting.

3.3.3 Safe handling of beryllium containing alloys

Beryllium poses a severe health risk when inhaled in large quantities. The main threat to the workers working with beryllium is to become sensitized to beryllium, which can cause serious chronic pulmonary disease. Only a small number of people are actually susceptible of becoming sensitized to the element, but it is impossible to identify these people in advance. Another possible health risk posed by beryllium inhalation is the carcinogenic nature of beryllium, which can cause lung cancer. (Administration 2006)

The protection of the workers from becoming sensitized to the element can be carried out by limiting the exposure to the element. This can be achieved by providing adequate ventilation so that the airborne concentrations are low enough to eliminate any adverse effects on the workers. (Harkness, Spiegelberg and Cribb 1990)

4 CASTING SIMULATION

The importance of casting simulation has increased significantly as the companies are striving for efficiency in their production. The correct use of casting simulation can cut the design times of castings along with their costs significantly, as simulations can replace expensive and time-consuming test castings. In addition the castings and the casting systems can be optimized with the help of simulation so that the properties of the castings can be maximized, the yields are increased and casting weight values minimized.

While casting is one of the oldest manufacturing processes it is also is one of the least understood. The basic principles of casting are simple, but when they are viewed in greater detail they are much more complex. As the computational power of computers has increased during the past two decades, the achievable accuracy has increased and calculation times have decreased so that simulation can be used to evaluate real world cases with high degrees of complexity.

While the potential accuracy of casting simulation has increased significantly during the past decade, the accuracy of the results still relies on knowing the accurate parameters for the simulation. If the input data for the simulation is incorrect, the results will also be incorrect. While the parameters will never be absolutely correct, it is very important to get them as close as possible to the correct values. When the values are close to the real values, the simulations should give a decently accurate representation of the real world. George E.P. Box has stated that, “All models are wrong, some are useful”. (Hinkkanen 2009)

4.1 The basic principles of casting simulation

Casting simulation in MAGMASOFT is based on FVM which is comparable with other “Finite Element Method (FEM) techniques, which for example, are often used to evaluate stresses in components. In the mathematical-methods the components which are evaluated are divided into a finite number of elements. Depending on the used simulation-method the elements can be of different shapes and sizes.

As with other mathematical-methods, casting simulations have the same workflow. The basic workflow consists of preprocessing, running the simulation, and post-processing of the simulation results.

4.1.1 Pre-processing

The pre-processing in casting simulation starts with defining the geometry of the castings. Today the geometries for the simulation processes are reasonably easy to define, as the geometrical data of the castings is most often available due to the fact that most castings are designed with the help of CAD programs. The CAD programs usually can provide the simulation programs with the suitably formulated geometries.

Before a simulation can be run there are still several phases which have to be accomplished before the whole simulation is defined. While most CAD-programs can provide a format which is readable by the simulation software, the geometry still has to be divided into an appropriate number of elements. Depending on the used simulation software, different kinds of element shapes are possible. MAGMASOFT currently only supports cube-shaped elements, which poses some restrictions on the achievable mesh. The basic principle of enmeshing geometries in MAGMASOFT is shown in Figure 6.

The number of elements used in simulations has increased during the past years due to the increases in computational power. The more elements the mesh for the geometry has, the higher the simulation accuracy will be, but the longer it will take to simulate the process. This means that the user of the software has to determine what is the needed accuracy of the simulation. It does not make any sense running simulations with too many elements, if the calculation times become unbearably long.

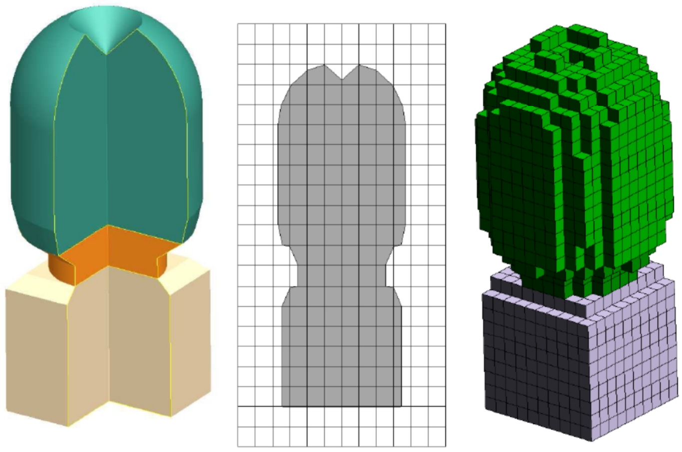

Figure 6 - Enmeshing of feeder geometry with several different material designations. (Mampaey 2001)

When the geometries have been successfully imported into the simulation software such as MAGMASOFT, the users have to define the specific volumes of the geometry with the necessary process and material data. The needed material data includes the physical properties of the materials for the volumes in the simulation and heat transfer coefficients for each material interface. The process data on the other hand includes all of the different timings of events, initial temperatures and pressure-curves to name a few.

Material data

The material data necessary to define the process conditions for the simulation includes the following physical properties:

- Melting and solidification temperatures
- Latent heat of fusion
- Solidification mechanism
- Specific heat as a function of temperature (Figure 7)
- Thermal conductivity as a function of temperature
- Density as a function of temperature (Figure 7)
- Solidification state as a function of temperature (Figure 8)

These properties have to be available to the simulation software for the simulation to be possible. When simulating the filling of molds, the viscosity and surface tension of the casting alloy melts should also be known as a function of temperature. If there is no data available for the viscosity and surface tension, the software can often provide an approximation of the values, if the needed initial data are available as a function of temperature.

The reliability of the simulations depends on the accuracy of the preliminary data, so it is important that the data used in the simulation models are correct. Often this means that some of the parameters and values need to be determined or checked. While the simulation programs often provide a material properties database, they often include only the most commonly used materials.

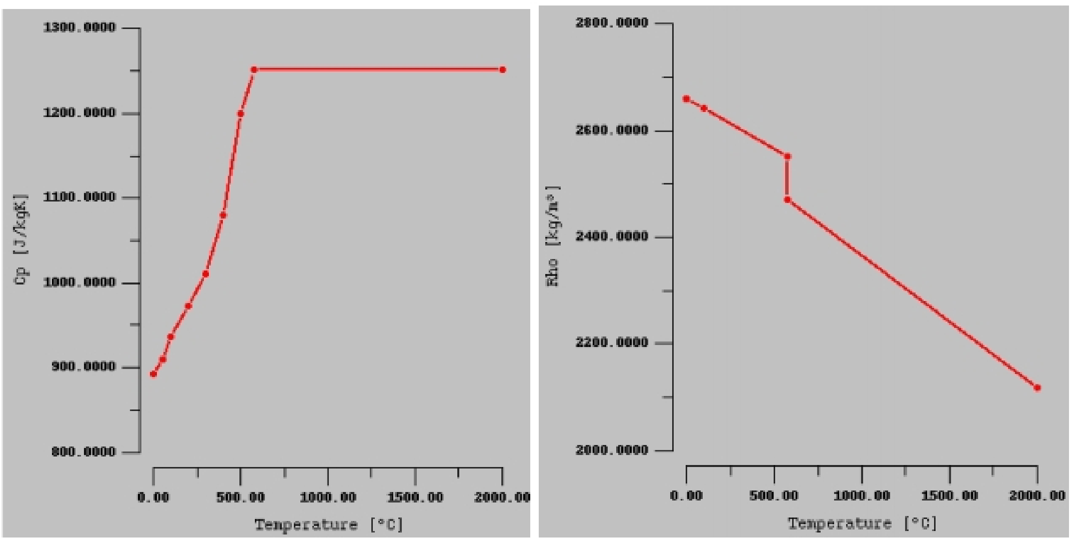

Figure 7 - The specific heat and density curves of AlSi12 as a function of temperature. (Hinkkanen 2009)

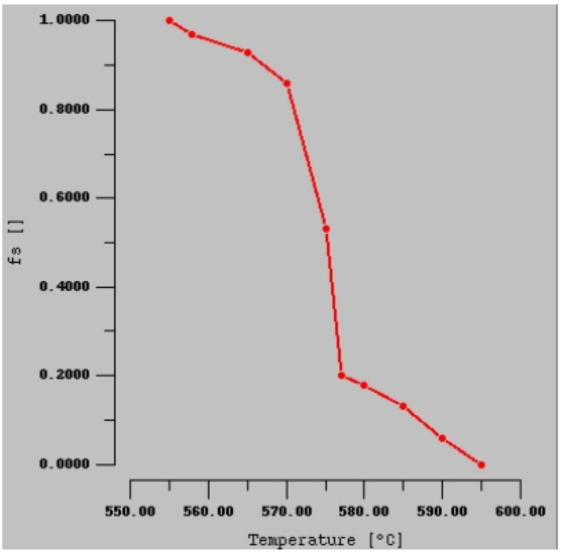

Figure 8 - Fraction solid curve as a function of temperature for AlSi10Mg. (Hinkkanen 2009)

Heat Transfer Coefficient (HTC)

The heat transfer coefficients (HTCs) across different surfaces are among the most important parameters in simulating permanent mold castings. In permanent mold casting the HTC is the most important parameter, which determines the cooling rate of the casting. If the HTC is not correct, the whole simulation will be incorrect and the results wrong.

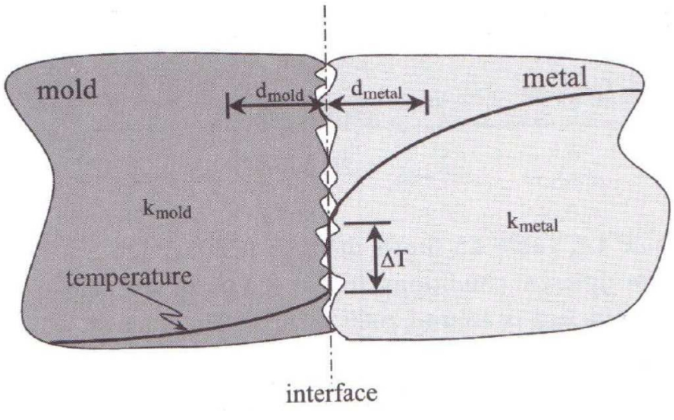

Figure 9 - A figure of the metal-mold interface. (Polyteknisk Forlag 2005)

The heat transfer coefficient determines the rate at which heat is transferred over material interfaces. One of these interfaces is the interface between the mold and metal. This interface is shown in Figure 9. The difficulty of determining the correct heat transfer coefficients comes from the fact that they are not constants, but depending on the interfaces they can be, for example, functions of temperature or time. Most commonly HTCs are functions of temperature.

The HTC of the mold-metal interface most commonly has its highest value when the cast metal is in liquid form and the value drops at some point during or after solidification. This drop can be caused by several different reasons. One of the reasons is an air gap forming between the mold and the solidifying and shrinking casting, causing an insulating air-pocket to form between the two materials. This insulating layer of air influences adversely the conduction of heat over the interface.

There are several other HTCs which have to be considered in addition to the mold-metal interface in low-pressure die casting. A HTC has to be assigned for every single material interface. (The University of Michigan; Missisippi State University 2005)

4.1.2 Simulation

There are several things which can be simulated in casting process. The main three simulation categories, into which the simulations can be divided, are filling, solidification and stress and strain simulations. The first two simulation categories are by far more common than the stress and strain simulations. The main reason for this is that the stress and strain simulation modules for the simulation programs are expensive and require lots of computational power as well as expertise in setting up the simulation and interpreting the results.

Filling simulation

The filling stage of the molds is a vital step in producing good castings. If the filling of the mold is not optimal, quality issues can be caused by premature solidification and air entrapment, to name a few reasons.

Filling simulations simulate the filling of molds. The filling simulation takes into account the conservation of momentum, mass and energy. The temperature dependent properties of molten metals cause challenges in filling simulations, which increases the need of calculation time to solve the problem how the molds actually are filled.

For accurate casting simulations, filling simulations are important for the end results. The filling simulations provide the solidification simulation with the correct temperature distribution in the casting. In addition the filling simulation brings the correct amount of heat into the mold when simulating permanent castings. If the filling of the mold is not simulated, the solidification simulation needs to use a homogenous heat distribution for the castings, which is far from the actual truth.

Solidification simulation

After sufficient amount of heat has been taken away from the molten metal, it will start to solidify after or even during the filling of the mold. Solidification modeling most often finds the solution to the energy equation, which takes into account the energy conservation laws. It has to be noted that the conservation of momentum and mass cannot be forgotten, either. For example, the convection can still move the molten or solidified areas within the castings.

Solidification simulations are the most common ones as they are easy and fast to run. Running the basic solidification simulations without the initial information from filling simulation will most often give a decent approximation of the problem areas of castings, giving the designers valuable feedback on their design. However, the solidification results can be considerably different when comparing them with reality, if they are produced without using the filling simulation-generated heat distributions, which improve this situation considerably.

Stress and strain simulation

The stress and strain simulations can be carried out after running the filling and solidification simulations for the studied case. The stress and strain simulations are usually run in a semi-coupled way where the thermal analysis and mechanical analysis are run in sequences. If not done this way, the simulations must be run simultaneously, which is much harder.

These simulation results can be used to evaluate the mechanical properties of the castings and the risks of distortion and hot tearing, to name a few uses.

Factors which are taken into account when calculating stress and strain simulations in castings:

- Linear thermal contraction
- Solid state phase transformations
- Shrinkage-dependent interfacial heat transfer
- Mold distortion
- Temperature dependent plasticity
- Hydrostatic pressure
- Crack formation

4.1.3 Post-processing

Before the simulation results can be analyzed, they have to be post-processed into a form which is easier to interpret as the raw simulation data is merely numeric in character. Most often the simulation results are post-processed so that they can be viewed as 3D-geometries. There are various different results which can be calculated from the simulation results to get them valuable for the users.

Possible post-processed results from filling simulation for each recorded time-step are e.g.:

- Air entrapment
- Filling pressure
- Filling temperatures
- Flow velocities (Figure 10)

As with filling simulation, there are several different kinds of results which can be calculated for different stages of solidification:

- Fraction solid and liquid (Figure 11)
- Temperature

At the end of solidification the following properties can be calculated just to name a few:

- Porosity (Figure 12)
- Niyama-values for estimating the tendency for porosity formation
- Feeding

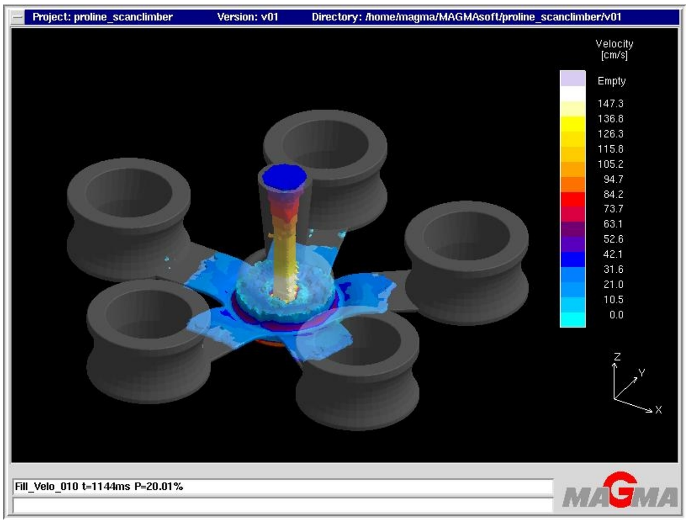

Figure 10 - Flow velocities in an iron casting during the mold filling stage.

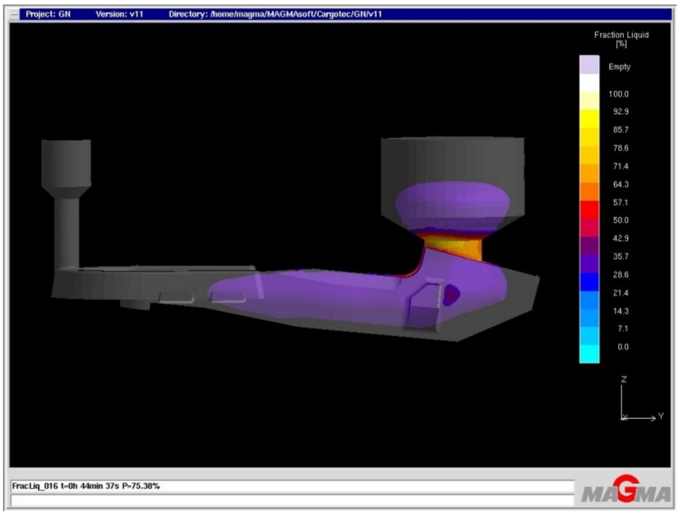

Figure 11 - Fraction liquid-simulation results for a steel casting during the solidification stage.

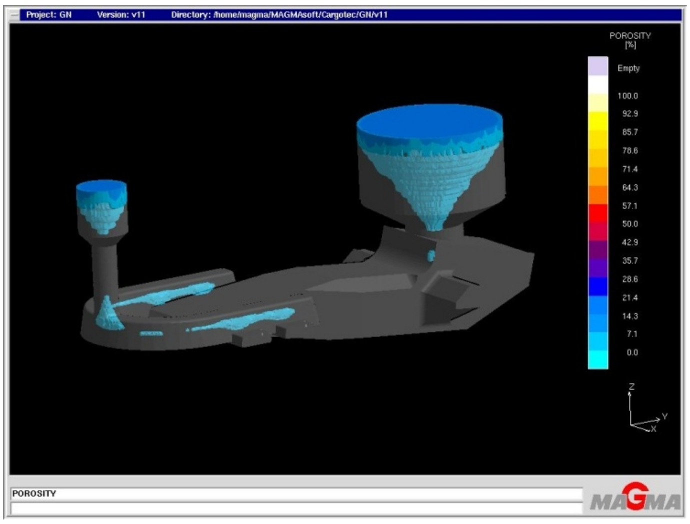

Figure 12- The porosity analysis of a large steel casting.

5 TEST MOLD DESIGN FOR EXPERIMENTAL STUDIES

As the main goal of this thesis was to verify and improve the simulation results of the low-pressure die casting process at Oras, it was necessary to make a test mold, which could be instrumented so that the simulation results could be verified. In the beginning of the project several basic principles for the mold were established.

The basic principles of the design of the mold for experiments were the following.

- Simple geometry for easy manufacturing
- Sufficient room for instrumentation
- Consistent behavior of the mold so that long testing runs with numerous cycles can be carried out without problems

The main idea behind the test mold design was to create a test mold which was simple and provided enough space for the thermocouples inside the mold assembly.

5.1 Geometry design principles

The main goal when designing the test mold for the experiments in this thesis was to provide a stable mold, which would be easy to manufacture, model and simulate.

5.1.1 Casting design

Various different casting geometries were evaluated during the design process, but at the end the most suitable geometry for the test casting turned out to be a plate. The dimensions for the plate were calculated from the modulus-restrains established in earlier studies and the restrictions of mold size for the casting machines.

The plate geometry for the castings was easy to manufacture and it was also easy to enmesh for the simulation in MAGMASOFT.

5.1.2 Gating design

The gating was designed with stable filling conditions in mind so that the simulations would have a good accuracy. The geometry of the gating for the mold was designed so that the molten metal would fill the cavities smoothly and with the correct relative speeds. The flow was also directed by adding several ingates at the bottom of the casting. These ingates would help to direct the flow of the molten metal so that it would be laminar when moving up in the cavity. The gating design also tried to eliminate the rapid changes in flow speed when the filling of the mold was at critical stages. The resulting mold design can be seen in Figure 13.

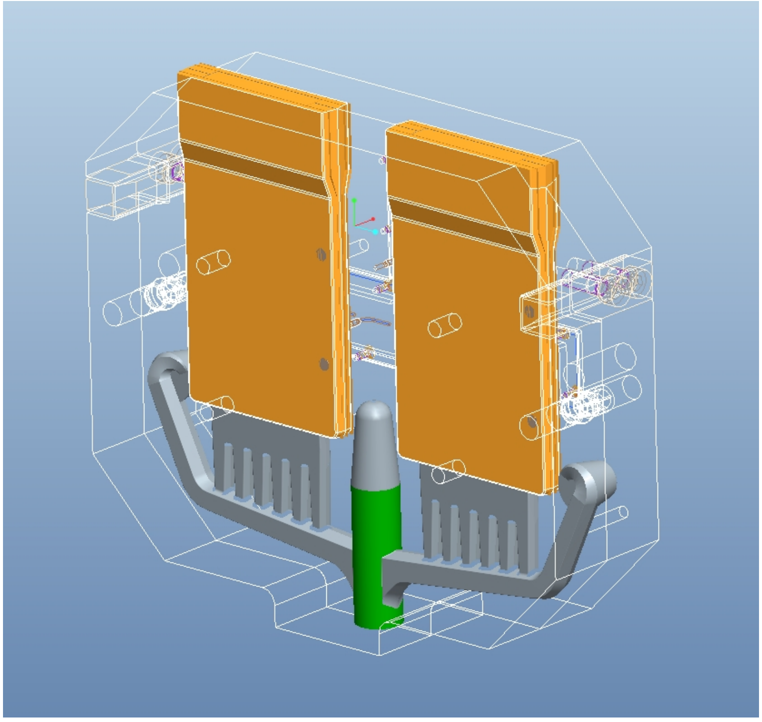

Figure 13 – The design of the instrumented mold.

5.2 Instrumentation design principles

When designing the instrumentation of the mold it was decided that a total of sixteen temperature measurement sites would be located in the mold, so that a sufficient amount of proper thermal data could be measured from the mold. The easiest way of doing this was to use two separate data loggers, both with 8 channels for thermocouples, one for each mold plate.

The mold was decided to be instrumented from the backsides of the mold plates. This was done by adding a in the back second cavity which could be sealed to the plate of the mold. The cavity would house the thermocouples and their wires used to measure the temperatures at various different positions and depths within the mold plates.

As the loggers need to be protected from the heat and moisture, they were detached from the mold plates and encased. The locations of the loggers were chosen to be close to the mold, as this would enable to make the thermocouple wires as short as possible. As the loggers were attached to the mold construction, they would move with the mold at all of the different phases of the casting cycle, removing the eventual bending and movements of the thermocouple wires. The locations of the logger enclosures can be seen in Figure 14.

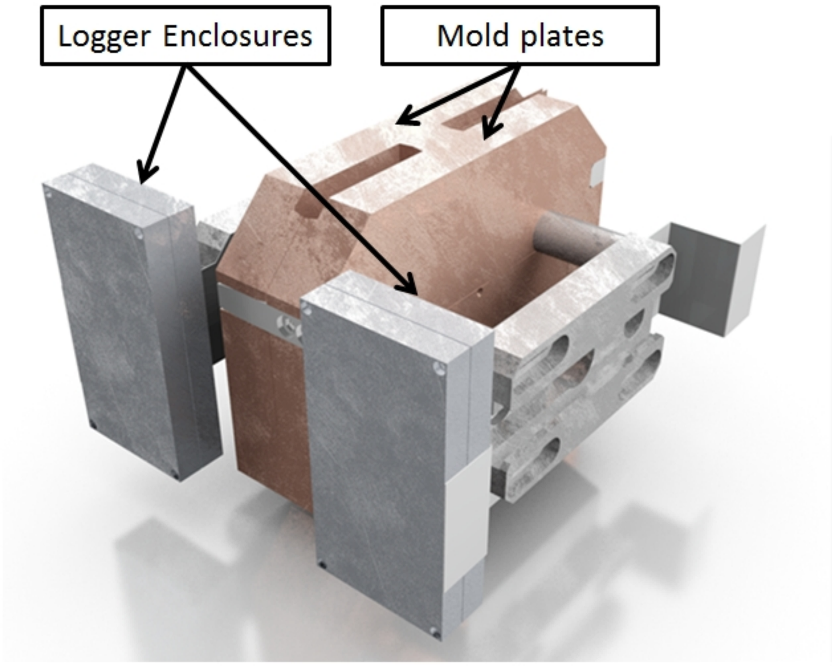

Figure 14 – The concept of the test mold with instrumentation.

5.2.1 Thermocouple placement

The thermocouples were placed of various different places and depths in the mold. The main goal in placing the different sensors was to provide sufficient thermal data from different areas of the mold, such as the gating-system and the castings. A total of 8 thermocouples were placed on each mold plate. Each plate had the same locations for the thermocouples, but the depths of the thermocouples were different on each side apart from one sensor which was identically placed on both sides.

6 IMPROVING THE ACCURACY OF SIMULATION RESULTS

There are several different parameters which influence the accuracy of casting simulations. In order to improve the accuracy the correctness of these parameters has to be verified so that they better represent the reality. Often the parameters and values provided by the simulation software are only approximations or represent the parameters from a different material or process. In general the process parameters are different in each foundry, and therefore it is vital to verify the parameters for each process that is strived to be simulated.

There are several different categories of parameters and values which should be verified and which can be improved in most cases. It is easiest to divide the parameters and values into three separate groups, material data, HTC data and process data.

Material data

The material data can be verified and improved by either carrying out the required measurements or by getting the values through the use of theoretical models. While the actual measurements will usually provide better results, the difficulty of some of the measurements may lead to the use of theoretical models instead of real measurements. The measurements involving the molten state materials can pose big challenges and problems. For example, the viscosity and surface tension of the melt can be hard to measure as a function of temperature. Some of the potential measurement methods for different material properties can be seen in Table 4.

Table 4 - Material properties and measuring methods.

Property	Measuring method
Density	Dilatometry
Heat capacity	Differential Scanning Calorimetry
Heat conductivity	Laser flash diffusivity
Liquidus and Solidus temperatures	Thermal analysis

HTC values

The heat transfer coefficient values can be determined with a few different methods. Depending on the situation, the HTC-values can be calculated from measured data through mathematical methods which rely on theoretical models. The other way is to test different HTC-values in the simulation software and to compare the temperature-time curves of the simulation to the measured values. Through trial and error the correct HTC-values can be found with a sufficient number of iterations.

Depending on the instrumentation and thermal data, several different HTCs can be determined. In this thesis the HTCs for the casting-mold and mold-dipping media interfaces were established through running sequential simulations and by adjusting the values between each iteration cycle.

Process data

The process data for the simulation can be verified through the measurements of the different parameters of the process. These include the filling pressure curves and the timing of the different cycle phases.

EXPERIMENTAL STUDIES

The verification and improvements of the simulation results were accomplished by conducting several different experiments. Materials testing was carried out at Tampere University of Technology, Jönköping University and at the Oras Oyj. foundry in Rauma.

7 STUDIES ON MATERIAL DATA

As stated earlier, it is vital to have the correct material data available in the simulation software. As some of the materials used in the simulated process were not included in the database delivered with MAGMASOFT, the models for some of the materials were only based on approximations and some were derived from the data for other similar materials.

Due to the lack of material data, it was crucial to update the database by describing the materials missing from the database with the needed accuracy. The level of required accuracy for the material data was determined by the impact of the material on the results. The materials whose properties have the most impact on the casting process in low-pressure die casting are the casting alloys and mold materials. Thus the highest degree of accuracy was required for the casting alloys and the mold materials themselves.

7.1 Casting alloys

As the casting alloys and their properties have a profound influence on the simulation results, it is crucial for them to have the correct material data for simulation. As the casting alloys and their properties need to be described in a broad temperature range, from room-temperature to well into the liquid-state, actual measurements for the properties would have been both difficult and expensive to perform. This is why the casting alloy data was improved through the use of theoretical models to simulate the needed properties. These simulated properties were then verified through thermal analysis of the alloys.

7.1.1 Theoretical models of copper alloys

The casting material properties were simulated by using the CAS-model (Copper alloy solidification model) developed at the Aalto University School of Engineering during the years 2002-2008. The CAS-model is based on the IDS-model (Interdendritic solidification of steels) which has been developed since 1984. In comparison with the IDS-model, the CAS-model is much more complex due to the fact that the solidification of copper alloys much more complex than the solidification of steels.

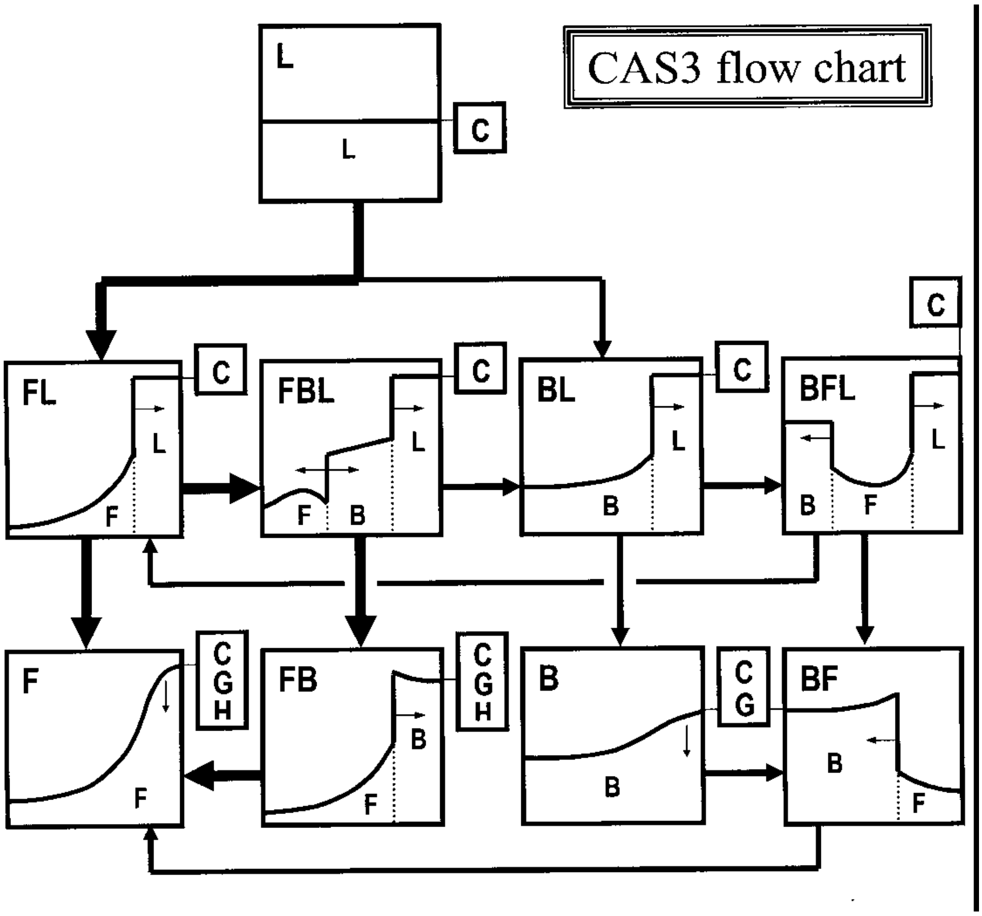

Figure 15 - Flow chart of the CAS-model showing the calculation modules of different phase region for multi-component copper alloys (L=liquid, F=FCC, B=BCC, C=Compound, G=Gamma, H=HCP). (Miettinen 2011)

The simulations for this thesis were carried by Jyrki Miettinen from Casim Consulting Oyj. As the CAS-model could not directly be used to simulate the materials used in the simulated Oras process, it was modified by adding the missing thermodynamic data so that the simulations for the needed compositions could be run.

With the CAS-model the thermodynamic, diffusion, and dendrite arm spacing-data can be calculated when the composition and cooling rate are known. Figure 15 shows the flow chart of the CAS-model.

7.1.2 Verification of the simulated properties by thermal analysis

The verification of the theoretical model results for the casting alloys was carried out with thermal analysis. The main goal of the thermal analysis was to verify the liquidus and solidus temperatures for both alloys. If the liquidus and solidus temperatures established through thermal analysis were reasonably close to the simulated values, the simulated data could be considered as suitable for use.

The thermal analysis measurements were carried out for both casting alloys at Oras. The compositions of both alloys were analyzed before the measurements to ensure that the compositions were within the specifications.

The measurements were carried out with insulated measurement cups equipped with s-type thermocouples so that the cooling curves of the alloys could be measured. Two successful measurements were accomplished on both alloys to ensure the reliability of the results.

The measurement equipment was set up next to the furnaces so that the metal could easily be poured into the measurement cups by using a hand ladle. After the metal had been poured into the measurement cups, it was allowed to cool down sufficiently so that the phase transformations which were of interest could be seen on the cooling curves. The measuring setup can be seen in Figures 16 and 17.

The different phase transformations in the material can be seen as cooling-rate changes in the thermal analysis. The phase transformation temperatures of interest in the casting materials were the liquidus and solidus temperatures. As apparent in Figure 18, the material cools rapidly to the liquidus temperature, after which the cooling rate drops and the temperature stabilizes. This is caused by the latent heat released by the solidifying material. The cooling-rate increases again after the material is completely solidified.

Figure 16 - The measurement setup for the thermal analysis of the casting alloys.

Figure 17 - The instrumentation for the thermal analysis of the casting alloys.

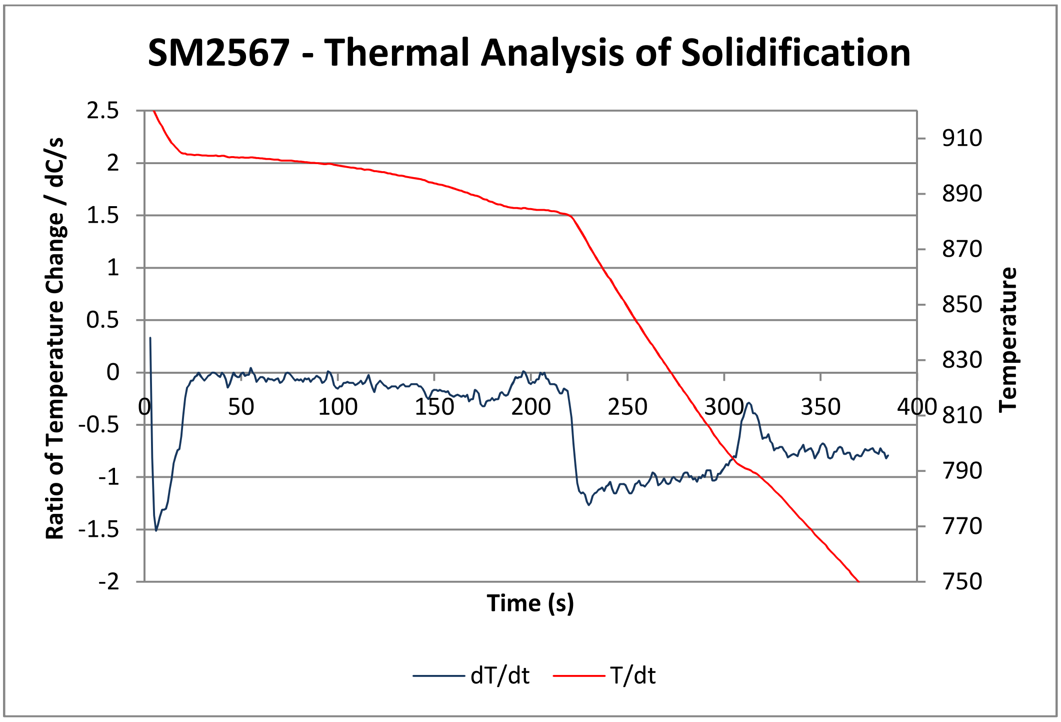

Figure 18 - The thermal analysis of one of the casting alloys.

7.2 Mold materials

The mold materials have a great influence on the solidification of castings and therefore they were tested and the data was improved to enhance the simulation accuracy. Two different mold materials were tested in order to establish what kind of impact they have in the casting process. The materials tested were the CuCrZr-alloy used at the Oras foundries and the more commonly used beryllium copper. Due to the lack of measuring equipment the measurements were conducted at Jönköping University. The samples were sent pre-cut and finished according to specification to Jönköping University where the actual measurements were performed by Toni Bogdanoff.

Three different properties of the mold materials were measured so that the descriptions for each material could be brought into MAGMASOFT. The thermal diffusivity, density and specific heat of the materials were all measured as functions of temperature. These values were also used in calculating the thermal conductivity of the mold materials. The mold materials were tested for the temperature range from room-temperature to 600 °C as the mold materials should never experience temperatures over 600 °C during their use.

7.2.1 Specific heat capacity

The specific heat capacity of the mold materials has a great influence on the simulation results in the low-pressure die casting process. It determines how much the mold will heat up during the casting cycles and how much heat it can withdraw from the castings.

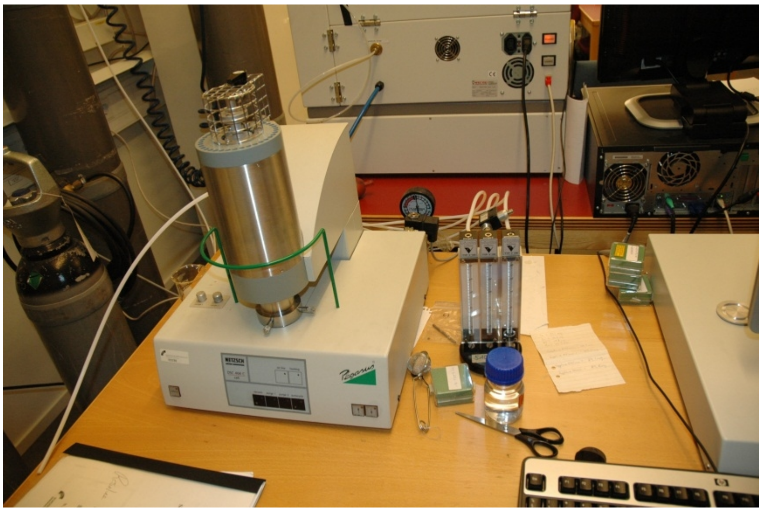

Figure 19 - The setup used to measure the specific heat capacity of the samples. (Bogdanoff 2011)

The specific heat capacity of the mold materials was measured at Jönköping University with their differential scanning calorimetry equipment (Figure 19).

7.2.2 Density

Density of the mold materials is also of interest when describing the materials for use in casting simulation programs. The density is also used to calculate other properties of the materials such as, e.g., the thermal conductivity.

The density of the mold materials was measured through the use of a dilatometer at Jönköping University (Figure 20). The dilatometer was used to measure the linear thermal elongation of the samples with increasing temperature. This data could then be used to calculate the density of the samples as a function of temperature, when the initial length and weight of the samples were known.

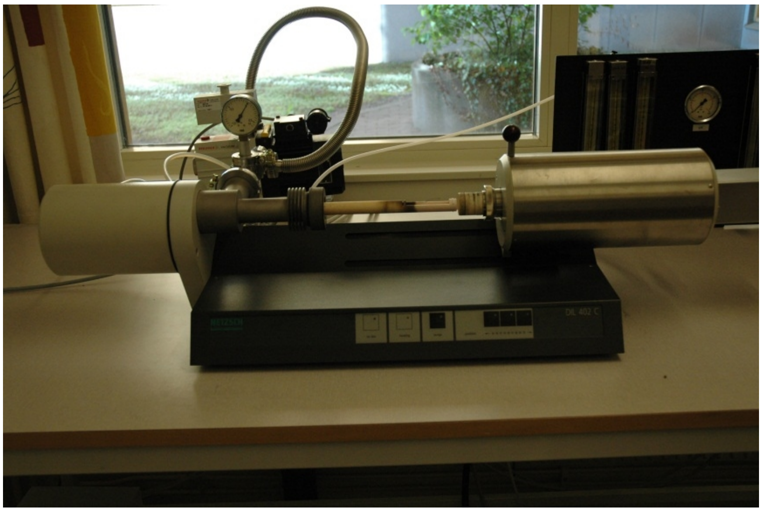

Figure 20 - The dilatometer used to measure the thermal elongation of the samples. (Bogdanoff 2011)

7.2.3 Thermal diffusivity

The thermal diffusivity of the samples was measured with a laser flash diffusivity equipment. The thermal diffusivity was measured to get the thermal conductivity values within the wanted temperature-range for both of the mold materials. These values were needed to describe the mold materials in the simulation software.

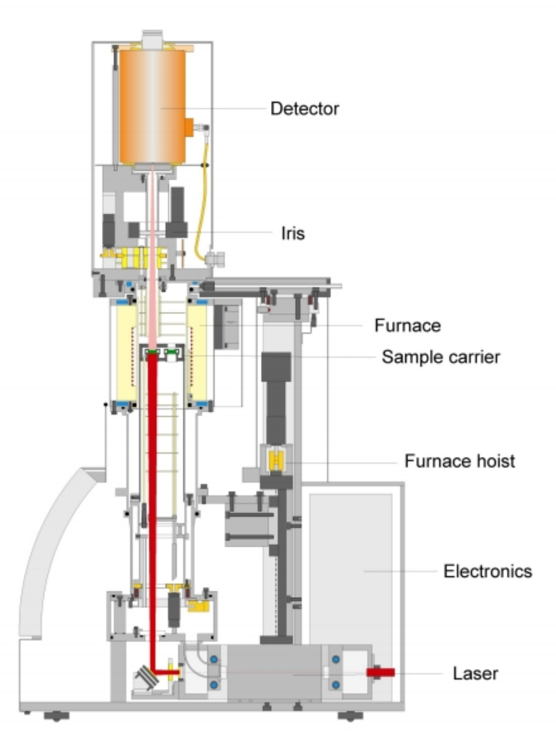

Figure 21 - The basic structure of laser flash diffusivity equipment. (Netzsch n.d.)

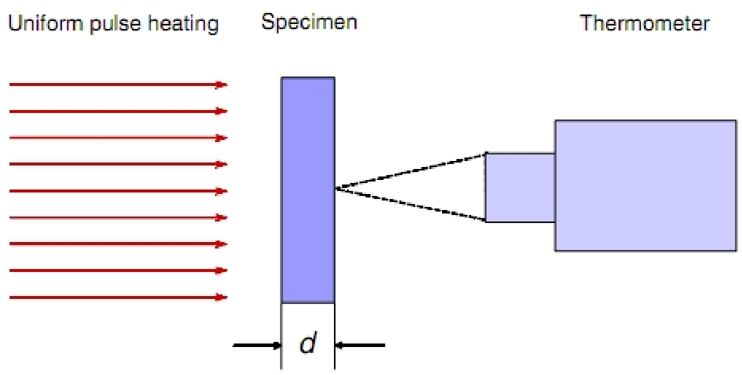

Figure 22 - Working principle in the measurement of the thermal diffusivity with laser flash diffusivity equipment. (Lenseis n.d.)

In laser flash diffusivity measurements the samples are subjected to precise laser pulses (Figures 21 and 22) and the temperature of the backside of the samples is measured with an IR sensor which can detect how much heat is transferred to the other side of the sample. When monitored continuously the thermal diffusivity can be calculated from the temperature change as a function of time. (Lenseis n.d.)

7.3 Core materials

The core materials were only compared with each other so that the differences between the different materials could be determined. As the core materials transfer only very small amounts of heat away from the casting when compared to the metallic mold materials, their influence on the results is so small that accurate models of the core sands are not as crucial as those of the mold materials.

7.3.1 Comparative testing of the thermal conductivity in sand materials

The different core materials were tested so that the differences between their thermal conductivities could be seen. No actual conductivity values were obtained during the measurements. These measurements were carried out in order to establish the eventual need for more accurate measurements on the core materials.

The comparative testing on the core materials was carried out on small sample cores which had been made at Oras. A total of five different compositions of cores were tested to establish whether there are any significant differences between the core materials.

7.3.2 The setup of experiments

The measuring equipment consisted of a hot-plate, a large copper plate which was used to eliminate the uneven heat distribution, two thermocouples, a data logger and a laptop computer (Figures 23, 24 and 25). In addition a few pieces of kaowool were used to insulate the surroundings of the samples while measuring.

The two thermocouples were used to measure both sides of the sample. The thermocouple on the bottom of the sample was used to ensure that the hot-plate provided a stable temperature. The second thermocouple was used to measure the temperature on top of the samples. The rate at which the temperature increases on top of the sample depends on the thermal conductivity of the samples.

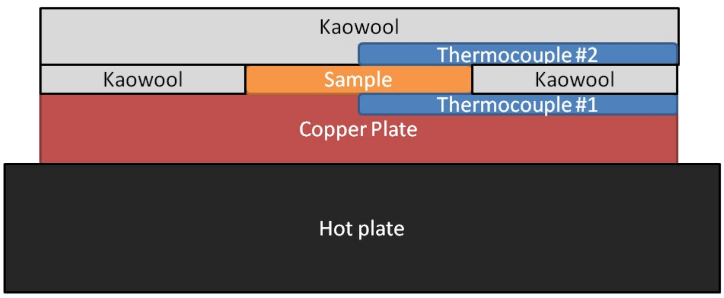

Figure 23 - The measurement setup for the thermal conductivity studies of the core sands.

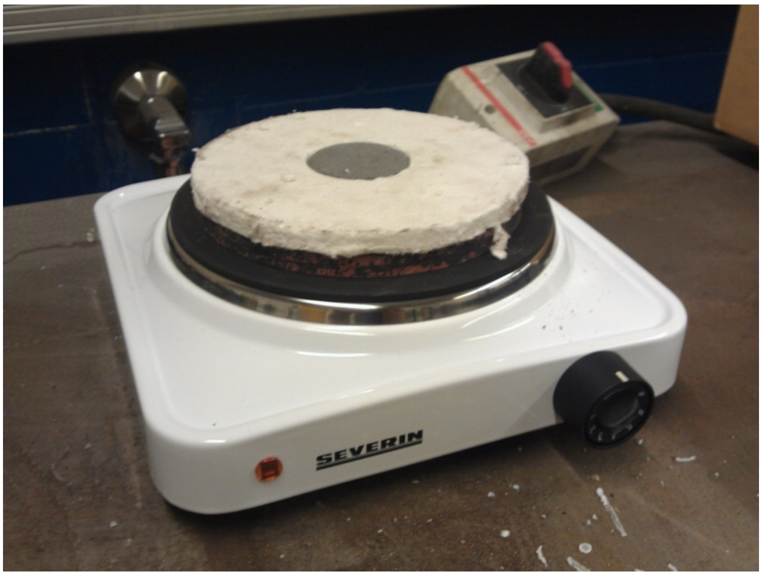

Figure 24 - The hot-plate with the insulation and core material sample placed inside the insulation ring in the thermal conductivity studies of core sands.

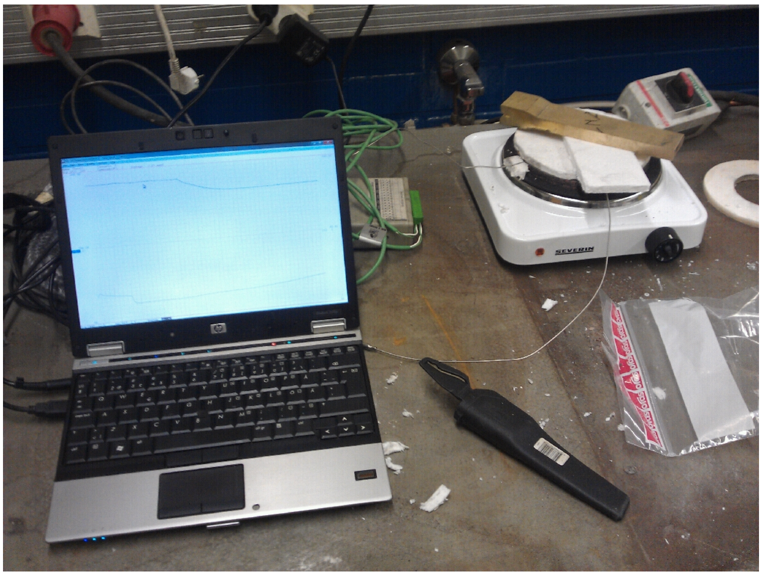

Figure 25 – The actual setup fo the measurement equipment ring in the thermal conductivity studies of core sands.

The measurements were carried out by heating up the copper plate to a stable temperature. During these measurements the temperature of ~185 ºC was used. The poor accuracy of the hot plate thermostat made the control of the temperature difficult, which may have caused some variation into the results. However, as only a comparative study of the conductivity was needed, the performed three measurements with each core material would give a good estimation on the conductivity.

As the stable temperature was reached, the logger was set to record the temperatures of the two thermocouples after which the core sample was placed on top of the copper plate. Immediately after placing the sample onto the copper plate, the second thermocouple was placed on top of the sample. Kaowool insulation was placed on top of the sample and thermocouple as quickly as possible. This insulation was placed there in a way which enabled the pressing of the thermocouple against the measuring surface for better contact and the exclusion of any external factors eventually influencing the measurement. The measurements were run as long as necessary for the samples to heat up close to the hot plate temperature.

7.3.3 Results

The measurement results were evaluated with two different criteria for each core material. An average heating rate for each material was calculated and the temperature-vs.-time-curves measured on the top surface of the samples for each material were compared.

Figure 26 shows the average heating rates for all of the different core materials. As is evident from the results, there are no significant differences between the thermal conductivities of the core materials. The differences are so small that they will have no significant effect on the heat transfer during the casting cycle. Figure 27 further suggests that there are no significant differences between the measured core materials in these tests.

A comparative measurement with a sample of the mold-material would have been very good in showing how low the thermal conductivity really is in the sand materials. Unfortunately a sample of the mold material could not be obtained in time for the testing.

While the measurements on the core materials do not reveal any differences in the thermal conductivities of the core materials, it is possible that at higher temperatures the differences are bigger. The temperatures during the casting process can rise up to 1000 ºC and of those temperatures the properties of the core materials can behave completely differently as there are many reactions which can have big influence on the casting results. The binders within the core materials will burn, releasing varying amounts of gases into the mold cavities and into the melt.

While the thermal conductivities of the sand materials don’t have any significant differences, cores from different sands have proven to have significant differences in practice. One of the possible explanations for this is the fact that the different binder systems react differently at higher temperatures, giving off different amounts of gases. As the pressure of the gases given out from the cores at high temperatures can have big effect on the feeding of the casting, the core materials can have a big impact on where the feeding problems may arise.

Fortunately newer versions of MAGMASOFT will include better simulation possibilities for the behavior of sand and core materials. The gases released by the cores will be taken into account in the newer versions, which will have an improving effect on the accuracy of simulations especially in this process. With the current version of MAGMASOFT it is not possible to simulate the behavior of the core materials with this accuracy.

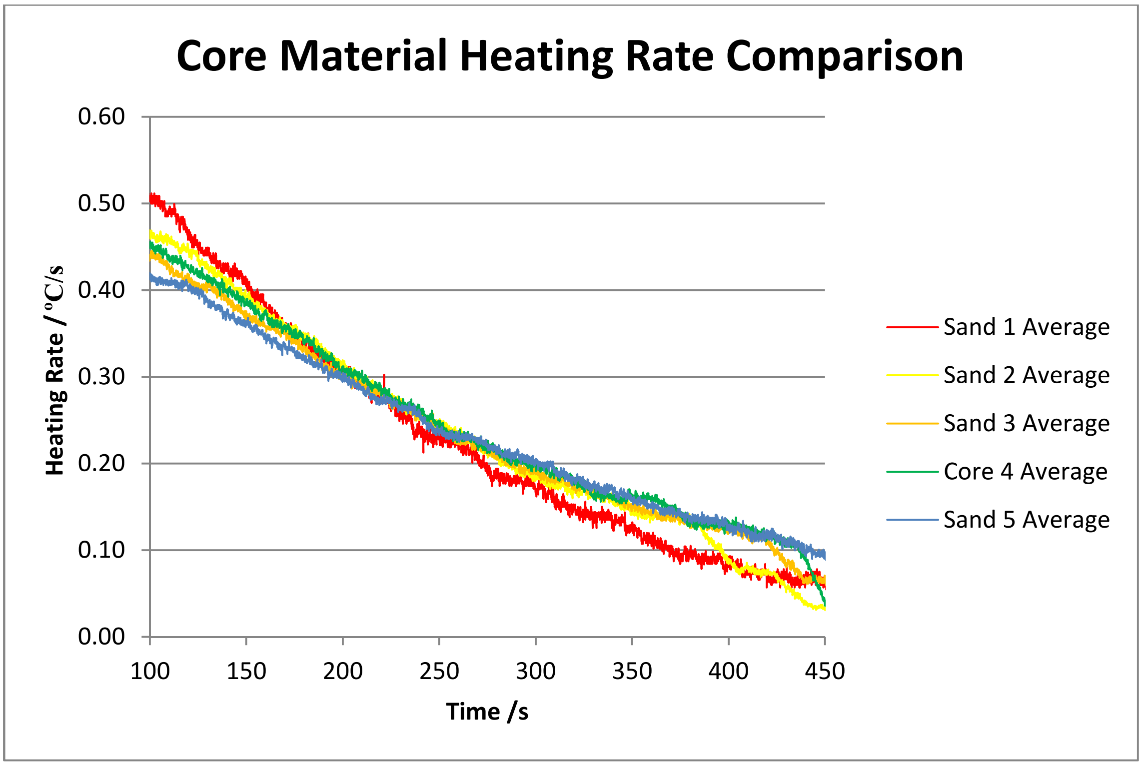

Figure 26 - The core material heating rate as measured at the top surface of the core sample in the comparative thermal conductivity measurements of core sands.

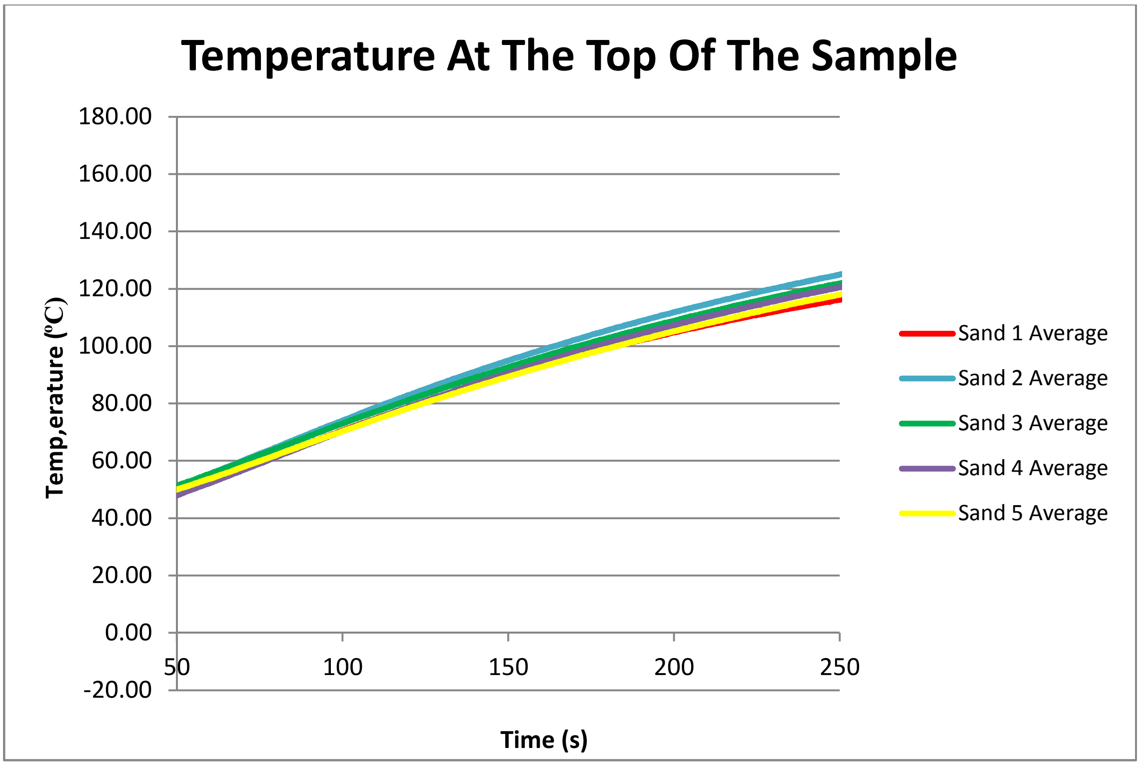

Figure 27 - The temperature vs. time measurements taken from the top surfaces of the core samples in the comparative thermal conductivity measurements of core sands.

8 CASTING EXPERIMENTS

The casting experiments were carried out at Oras Foundry on the two studied alloys using two different casting machines. The mold was also manufactured and instrumented at Oras tool shop.

8.1 Manufacture of the test mold

8.1.1 Machining the mold

The test mold was machined from wrought billets of the mold material. The mold material used for the mold was the standard material used at the foundry, CuCrZr. The mold plates were machined in two different stages, as both sides of the mold had to be machined. The cavities for the castings and the gating system were machined onto the front sides of the mold plates and the cavities for the instrumentation were machined on the backsides. Figures 28 and 29 show the molds in different stages of manufacturing.

8.1.2 Instrumentation of the mold

The instrumentation of the mold was carried out by using K-type thermocouples. The thermocouples used in this project were produced with thin tips in order to improve the sensitivity of the thermocouples to the changes in temperature.

The thermocouples were placed in drilled holes which provided the correct measuring points. The thermocouples were secured mechanically to the mold in order to prevent their movement during testing and to ensure the proper contact to the mold at all times. A thermal compound was used in one of the mold plates in order to establish the influence of a silicon-based thermal compound on the results. Figure 30 shows the thermocouples installed into the mold plate.

The wires of the thermocouples were secured within the instrumentation cavity of the mold so that manipulating the wires outside the mold would not break or move them. The instrumentation cavity of the mold was covered with a steel cover which had a hole, allowing the thermocouple wires to pass through. The cover plate was sealed so that no moisture could enter the cavity during the use and influence the results.

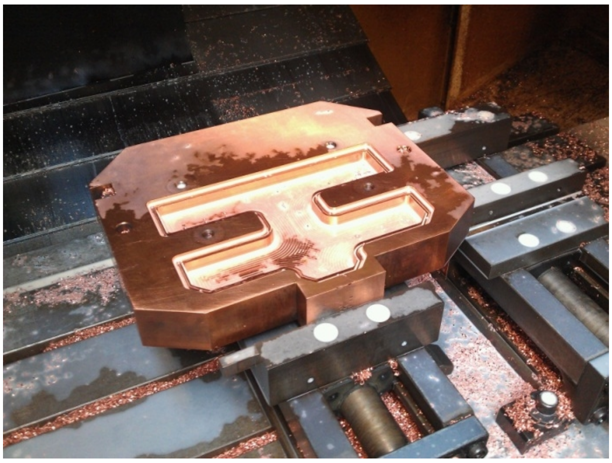

Figure 28 - The back side of the test mold plate with the instrumentation cavity.

Figure 29 - The sample cavities of the instrumented test molds.

Figure 30 - Instrumentation of the mold

Figure 31 - Protection of the thermocouple wires in the test mold.

The thermocouple wires were routed to the data logger enclosure, which was located behind the mold. Even if the thermocouple wires were rated for high-temperature use, they were further shielded with a heat resistant braided sleeve (Figure 31). This sleeving also made it easier to organize the wires.

The logger enclosure had two openings through which the necessary cables could pass. The thermocouple wires were brought into the enclosure through a hole at the back of the enclosure (Figure 32). The necessary power- and USB-cables for the data logger were brought into the enclosure through a smaller hole on the side of the enclosure.

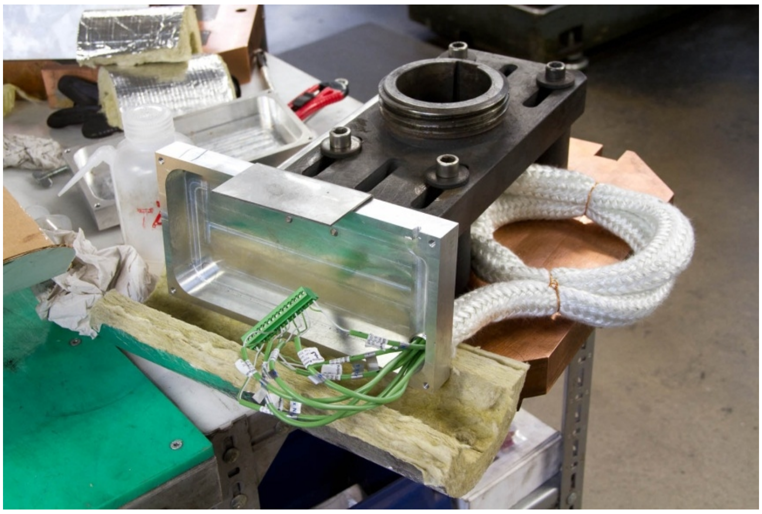

Figure 32 - Wiring of the thermocouples to the data logger enclosure for the casting experiments.

Enclosures for the data loggers were necessary due to the high temperatures and levels of humidity in the casting environment. The data logger enclosures were machined from aluminum and they were sealed from the environment with O-ring gaskets. As aluminum conducts heat very well, it was also necessary to shield the aluminum enclosure from the heat with additional insulation.

8.1.3 Mold setup

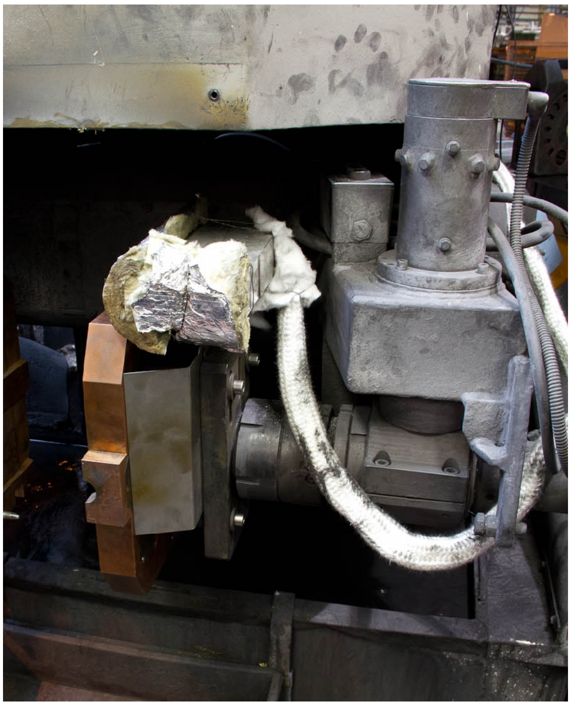

Figure 33 - The protection of the instrumentation and wiring of the molds when attached to the casting machine for the casting experiments.

Figure 34 - The computer setup used to record the measurements.

The data loggers were attached onto fixtures on the mold assembly. These fixtures were also used as heat shields for the wiring. The fixture was designed so that a part of it would guide the heat from the furnace away from the wires during casting.

The data loggers were connected to a laptop which was used to record the data (Figure 34). The data loggers could also have been installed to work off-line as well, but having the real time measurements visible during testing helped in determining whether the process was stable enough for the measurements.

The wiring of the data loggers was routed through the casting machine so that the wires would not interfere with the motions of the casting machine (Figure 33). The length of the wires posed some difficulties while routing, as the casting machines make quite large movements during the casting cycles.

8.2 The casting experiments

The goal of the casting experiments was to provide adequate amount of thermal data which could then be compared with the data produced via simulation. The goal was to cast sufficiently long series for the measurements to stabilize. The measurements were repeated with both casting alloys and for both coating systems.

The process parameters were established when the test mold was first used with the instrumentation. This way the stability of the process could be confirmed with the chosen parameters. When the parameters were established, the same values were used in all consequent tests with some small adjustments when casting with the second casting machine.

Some of the differences in process parameters for the two casting machines were also caused by the operator. Therefore the results between the different machines are not directly comparable. This only causes the need to calibrate the simulations for each casting alloy separately.

The measurements were carried out so that at least ten successfull cycles were cast in succession so that the process would have sufficient time to stabilize. All measurements besides the initial testing were carried out during two working shifts at the foundry. Some of the test castings can be seen in Figure 35. Figure 36 shows some of the measured thermal data from the casting experiments. The figure shows a total of eight different channels of temperature data over time. A total of 12 cycles were run in succession for these measurements.

Figure 35 - Test castings produced in the casting experiments

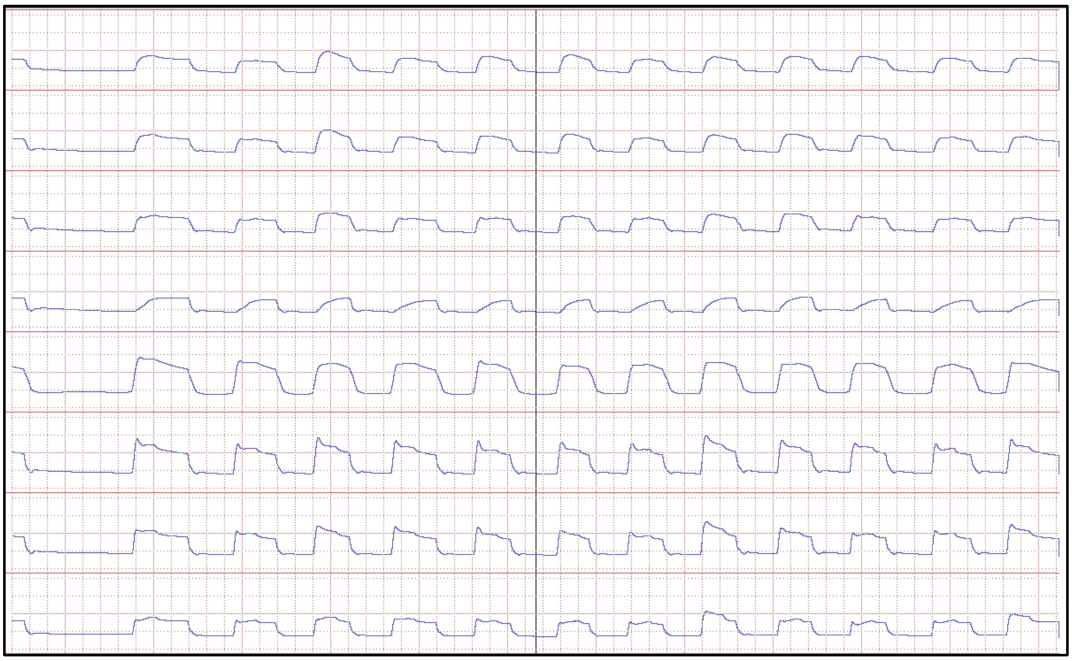

Figure 36 - Some measurement data from casting experiments recorded by the loggers

9 RESULTS OF IMPROVED MATERIAL DATA AND PROCESS PARAMETERS

9.1 Improved material data and process parameters

During the course of this project, most of the vital material data and process parameters were updated for the simulations. As the accuracy of the material data and process parameters was improved the simulation results have also improved significantly.

9.1.1 Casting alloys

While earlier there was only one casting alloy material described in the software for the Oras simulations, two new materials were described in order to improve the simulation results for both alloys. One of these new materials was the low lead alloy and the other was a more accurate material for the lead-containing alloy.

As was apparent after the simulated properties and the thermal analysis of both alloys, there was a significant difference to the originally used material model in both cases. The simulated properties and thermal analysis of the low-lead alloy provided new insight into many of the issues, which are only existent with this new alloy. While earlier it was believed that both used alloys should perform similarly and have similar properties, it was proven that the low-lead alloy had higher melting temperatures when compared to the normally used lead containing yellow brass.

9.1.2 Mold materials

Originally the simulations were run with only approximated material data of the mold material. After the project two new mold materials have been described into the software database, the currently used alloy and a beryllium copper alternative. The reason for describing both materials into the software database is to reveal whether the unusual mold material used by Oras is contributing to some casting faults and problems.

9.1.3 Core materials

As the project was carried out before a new version of MAGMASOFT was released, it was decided that describing the core materials was not as important as the description of the other system materials. The main reason for this is the addition of large amounts of new research-verified material data on different core and mold materials to the new coming version of the software. Therefore only a comparative test was carried out so that the differences between the different core materials could be determined. If significant differences between the materials would have been revealed, the importance of modeling the core materials into the software database would have been re-evaluated. Within a few years MAGMASOFT will provide better simulation of core materials into the software. With the new software version it would be wise to reconsider the need of improving the core material data.

9.1.4 Heat transfer coefficients

Heat transfer coefficients were in the core of research in this project as they have the strongest influence on low-pressure die casting simulation results. The HTCs were improved by running the simulations with different HTC-profiles and by improving the accuracy over several iterations of the coefficients.

This phase of the project demanded high computational power, which was available with a workstation provided by MAGMASOFT. A total of 38 iterations were run in order to improve the accuracy of the HTC-values.

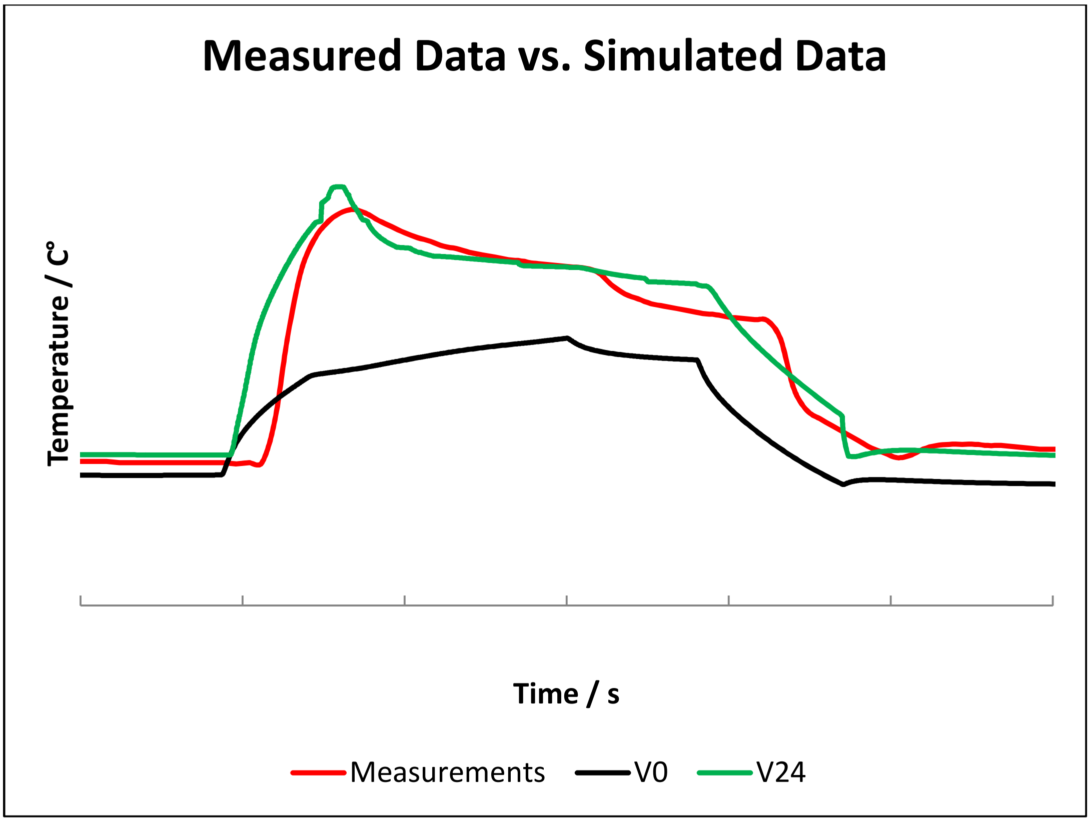

Figure 37 - Comparison of the measured temperature-time profile data with the new (V24) and old (V0) simulated profile

As is apparent in Figure 37, the original HTCs used for the simulation were not correct. The V24 HTC value provided a much better consistency with the measured results. Many different aspects of the HTCs were rethought during the process of improving the consistency and accuracy of simulation, which made the resulting HTCs to differ considerably from the originally used values.

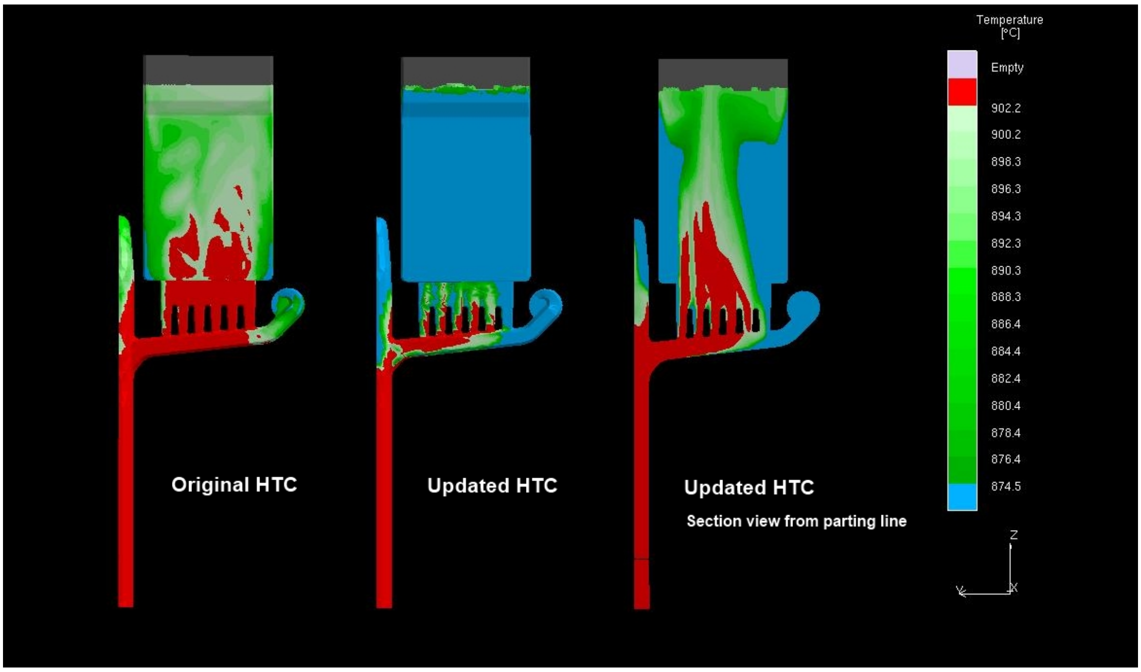

Figure 38 - Comparison of the temperature distribution during the filling of the test mold obtained in the simulations. The red areas are still completely in the liquid-state, the shades of green are partially solidified and the blue areas are completely solidified.

There is a clear difference in the melt temperature distributions in the filling simulation of the test mold, as is evident in Figure 38. With the updated HTC-values, the simulation results are completely different when compared to the simulations run with the initially provided HTC-values. With the originally provided HTC-values the casting is still almost completely in the liquid-state at this point of filling. With the new HTC-values the casting is already mostly solidified, represented by the blue areas, at the same exact point of filling.

9.2 Simulation setup

Work was also carried out for improving the setup of the simulation. Previously, the geometrical models of the casting nozzle were left out of the simulation, leading to incorrect temperatures for the casting alloy entering the mold. The temperatures of the melt at the top parts of the nozzle were verified during the casting experiments with the use of an instrumented nozzle. The temperatures seen in the new simulations were highly similar to the measured values.

While the addition of the nozzle to the simulations increased the accuracy of the simulations by some degree, it also increased the number of cells which have to be simulated and prolonged the simulation time.

9.3 Further verification of the simulation results

In this work the simulation results have been verified by comparing the simulated results to the temperature-time profiles measured with the instrumented mold. The simulation results were also verified by simulating other production castings and their molds by comparing those simulation results to the produced castings.

A couple of production stage castings were selected to verify the simulation results. Both castings were challenging in their own way, which made them interesting cases to simulate.

When simulated with the original dataset provided with the software, the simulation results represented the reality only poorly. The simulations with the original dataset completely failed to reveal the common problems related to these castings. Mostly this was due to the wrong HTC-values.

When using the simulation software with the improved dataset, the simulation results represented the reality much better. Currently it seems that many of the earlier unexplained problems related to these castings can be explained through the use of the simulation results obtained with the new dataset.

10 CONCLUSIONS

The present project has both verified and improved the simulation results for the low-pressure die casting process at Oras Oyj. The improvement of the data used for simulation has had significant effects on the simulation results. Due to this improvement in accuracy, casting simulation can be used as a better tool guiding the design of castings and tooling than before the project. Earlier the simulations could only be used to identify possible locations for feeding problems, but with the new data the filling behavior and the solidification of the castings can be evaluated with high accuracy.

With the use of simulation and tool development a better level of process know-how can be achieved and product designs can be better optimized for casting. This is possible due to the added knowledge of the casting process and having a tool which can be used to easily test changes in design and process parameters.

Simulation can also be used in the development of the casting process, as the influence of the different process parameters can be determined. With this information the process can be optimized.

10.1 Future areas of research

While most data acquired during this project are universal for all castings produced with the studied materials, some of the process parameters, such as cycle timings and HTCs, are not the same for all castings.

10.1.1 Improvements to simulation accuracy

The casting simulation accuracy can further be improved by fine-tuning the simulation parameters and data over time by comparing the simulation results to the results obtained with real castings. As this project only used a few different geometries to improve and verify the data used for simulations, it is apparent that the data can be further improved by using more references.

The instrumentation of other well-known molds would provide valuable data for the further tuning of the simulation software, as currently the only useful thermal data from the molds have been measured during this project with one mold. When more thermal data from different molds exist, this data can be used to improve the HTC-curves for simulation. This would further improve the simulation results.

When new materials are introduced to the process, they should also be described into the software in the same way as the new materials were described during this project. This includes the possible new casting alloys as well as new mold and core materials.

10.1.2 Improvements for process control and management

The instrumented production molds could also be used for the process control and for the management of the casting processes. The actual casting times can easily be seen and checked from the thermal data measured from the molds and the actual mold temperatures can be seen more reliably. The mold temperature data could be used to control the dipping time of the mold so that a stable casting temperature for the mold could be sustained through the whole casting process.

In the future it may also be possible to use the thermal data measured from the molds to fine-tune the filling pressure vs. time curves of the casting machines. It would be fairly easy to see how the molds are filled and this data could be used to adjust the curves for better filling behavior.

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