Slag inclusion formation during solidification of Steel alloys and in cast iron

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Licentiate Thesis

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Abstract

This thesis explores the formation of segregation and inclusions during solidification of steel and cast iron. A better understanding of the formation mechanism should result in decreasing fraction of defects during solidification of ingot and strand material.

Density driven macrosegregation was studied both experimentally and theoretically to see the effect of channel segregation on the total segregation. Formation of these pencil-like segregations is due to natural convection in the solidifying metal caused by liquid enrichment of elements with lower density compared to the bulk. It is suggested to change the composition to compensate for this density difference.

Inclusion precipitation can be finite by limitations in segregation. Saturated liquid is found in the last solidified areas, often between dendrites. Here the enrichment of the liquid is possible due to microsegregation. Meanwhile crystals form and solidify the elements with low solubility in the solid is pushed out in the remaining liquid. Soon the liquid is saturated to the level where spontaneous formation of inclusions occurs. Microstructure studies by aid of SEM and micro-probe measurements are analysed to find at what point during solidification process the inclusions start to form. In steel making this formation has a detrimental effect on the mechanical properties in contrary to the production of nodular cast iron where the inclusions have a beneficial effect on the graphite formation.

Inoculation of cast iron aims at reaching higher number density of graphite nodules, nodule morphology modification and control of nodule distribution during solidification. Late precipitation of nucleation sites has shown to have a positive impact on preventing chill. To find the most potent inoculation agent different additives were tested. Special effort has been made to analyse the effect of oxides and sulphides as nucleation sites.

Descriptors: solidification, segregation, precipitation, inclusions, inoculation, EPMA

Supplements

The thesis includes the following supplements

Supplement 1

Crack formation during continuous casting of tool steel
A. Lagerstedt, S. Adolfi and H. Fredriksson
Trans. Indian Inst. Met. Vol. 58, No. 4, August 2005, pp. 671 – 678

I performed the hot-tensile tests, evaluation and part of report writing

Supplement 2

Macrosegregation in ingot cast tool steel
A. Lagerstedt, J. Sarnet, S. Adolfi and H. Fredriksson
ISRN KTH-MG-INR-04:09 SE
TRITA-MG 2004:09

I took part in all experiments and part of final evaluation and report writing. In particular I performed the temperature measurements and EPMA analysis

Supplement 3

A thermodynamic analysis of the inoculation process
L. Magnusson, S. Adolfi and H. Fredriksson
ISRN KTH-MG-INR-06:03 SE
TRITA-MG 2006:03

I performed the experimental part and together with Lena Magnusson the theoretical evaluation

Supplement 4

MnS precipitation during solidification in presence of oxide nuclei
S. Adolfi, K. Mori and H. Fredriksson
Accepted to the 5th Decennial International Conference on Solidification Processing

I performed the experiments and report writing

Contents

1 Introduction

The aim of this study was to analyse the solidification process in steel alloys and cast iron. Focus has been on segregation and defects and their formation mechanism. Both experimental and theoretical method to analyse this has been used. A great part of the work has been to design the proper experiment. The experimental outcomes are used for further theoretical work.

During solidification of steel ingots and strand compositional variations referred to as macrosegregation range in scale from several millimetres to centimetres or even metres. The in-homogenous distribution of alloy elements have a detrimental impact on the following processing behaviour and the material properties and can lead to rejection of cast components or processed products. The formation of these variations is driven by natural convection where hot metal will flow upward inside the centre of the ingot and cooler solidifying liquid will grow heavier in density and flow downward the mould wall. At this stage some crystal with lower liquidus temperature can remelt while in contact with the high-temperature melt leading to channel formation where highly segregated liquid will flow upwards due to its lower density. During solidification crystals will freeze at the solidus temperature and gradually form a solid. This solid will continue to grow meanwhile the remaining liquid will be enriched by elements with lower solubility in solid phase compared to the liquid. This enrichment or commonly referred to as microsegregation will open up for precipitation of other phases, inclusions which benefit from the saturation of alloying elements.

Hot cracks are often the result from the solidification process. The material will go through a brittle to ductile transformation during solidification. The brittle region causes this crack formation. This brittleness is caused by the presence of thin liquid films in the interdendritic region at the crystal boundaries.[1] These are often type II MnS inclusions. By means of hot-tensile-tests, DTA and Electron Probe Micro-analysis the proper material data can be found for further theoretical analysis on crack- and inclusion formation. Inclusions in steel are categorized according to type (chemical composition) and morphology (shape). They origin either from before casting or they spontaneously precipitate during solidification. The first case is often a result from secondary metallurgy and can be an effect of slag or mould material being dragged into the liquid steel. This type is often referred to as macro slag. Precipitation of inclusion during solidification is possible when the supersaturation needed to form a certain compound is reached in the liquid and the formation facilitates by presence of small nuclei, mainly of oxide type. One of the most common inclusions is the MnS. Early it was discovered by Sims and Dahle,[2] they are of different morphology due to formation process. They classified the globular shaped as type I, enveloped thin sheeted as type II and the faceted ones as type III. Later work made by Fredriksson and Hillert,[3] revise this classification by adding the type IV morphology, a lamellar eutectic structured MnS. They suggest that the formation of types I and II are by a monotectic reaction where MnS forms as a liquid phase. Types III and IV are a eutectic reaction where MnS forms a crystalline phase. A monotectic reaction is a process in which a melt gives a solid phase and another liquid phase, $L_1 \rightarrow \alpha + L_2$. A eutectic reaction is a solidification process in which a liquid solidifies to two solid phases, L→α+β. The type of MnS inclusion depends on many variables. The main factors are: cooling rate, concentrations of Mn and S in the melt, the solubilities of the alloying elements in molten MnS + Fe and the deoxidation process of the melt. Common deoxidants are Al and Si. Another method to reduce O concentration is vacuum degassing.

During solidification inclusions are pushed in front, entrapped or engulfed by the solidifying front. Stefanescu et al.,[4] explain there exist a critical velocity of the planar solid – liquid interface below which particles are pushed ahead of the advancing front and above which particle engulfment occurs. Engulfment is used to describe incorporation of a particle (i.e. inclusion) by a planar interface and entrapment is used to explain how particles incorporate between cells and dendrites. Engulfment will normally lead to a uniform particle distribution, while pushing will result in particle segregation. Later studies by Stefanescu et al.[5] show that particle interaction with dendritic solid – liquid fronts can be explained with similar controlling parameters as for planar fronts. Based on dendrite tip radius, particle radius, natural convection induced liquid velocity, V_L, and the solidification velocity, V_{SL}, engulfment or entrapment occurs. Engulfment can occur if convection is low and surface velocity is high. Slow interface velocity result in particle being entrapped between dendrite arms. However if V_L is high but V_{SL} is small the particle will be pushed in front of the interface. These types of defects in steel production should be possible to decrease by better understanding on the formation mechanism.

Precipitation of oxides and sulphides has a beneficial effect on the graphite formation in production of nodular cast iron. The inclusions act as nucleation sites for graphite. By addition of different inoculation agents we can promote nodularity, refine the graphite structure and suppress carbide formation. In earlier work by Skaland,[6] it is suggested that different oxides and sulphides may increase the inoculation effect. Oxide and sulphide inclusions which are formed after addition of the inoculants act as nucleation sites for graphite nodules. To find the most potent inoculants we studied the nucleation process of graphite in presence of different inoculation agents. In contrary to inclusions formed during steel making precipitation of oxides and sulphides is most wanted.

2 Experimental methods

2.1 Material preparation

The material used in this thesis work is presented in table 1, supplement 4. Steel A is represented by one octagonal 12 ton ingot and one rectangular 10 ton ingot produced by uphill casting at Scana Steel Björneborg AB. Steel B comes from a continuous casting experiment carried out in slab caster 2 at SSAB Oxelösund AB. Steel C is a aluminium-killed 6 ton ingot produced by uphill casting at Ovako AB. Ingots were cold sawed to pieces in order to allow for sulphur printing and drilling for chemical composition to obtain the segregation pattern of C and S. The old but well known Sulphur printing technique was re-discovered and prints were made on sawed surfaces in order to obtain macrographs of the ingot structure. To get as detailed information as possible from the prints some surfaces was milled to give good sharpness. Photo paper was soaked in 5% sulphuric acid and rolled on to the metal surface in good contact. The prints are taken at the vertical cross section. Sample drilling was performed over the vertical cross section to obtain the segregation pattern of C and S.

Test with different inoculation additives are made on a base alloy of white nodular vast iron, presented in table 1, supplement 3.

2.2 Thermal properties

2.2.1 Differential Thermal Analysis

Differential Thermal Analysis, DTA was used to study the solidification process. The result is used as in-data for further theoretical calculations. During heating and cooling the sample temperature was measured and any transformation will be shown as a change in temperature compared to a known reference state. The technique is to measure the difference in temperature between the specimen and a known reference which are exposed to the same heating schedule. The reference could be any material with about the same thermal mass as the sample, which undergoes no transformations in the temperature range of interest. When the sample undergoes a transformation it will either absorb or release heat. The thermocouple will detect and indicate if the transformation is "exothermic" on a plot of temperature versus time. Heating rate is an important consideration in this investigation. Slower heating rate will more accurately depict the onset temperature of a transformation. Furthermore two transformations which are very close in temperature range may be mistaken for a single transformation under rapid heating rate. Measurements were performed using a resistant heated tube furnace. A graphite cylinder was place around the alumina crucible both to be used as reference but also to prevent convection in the melt. A constant heating and cooling rate of 10°C/min was used. Argon is used as shield gas. Temperature was measured by PtRh10%-Pt thermocouples. Calibration was performed with pure silver resulting in corrections of about +3°C and the measuring device work with an accuracy of ± 1°C. Sample dimension was 7 mm in diameter, 14 mm in height with a 3 mm wide and 9 mm deep centre hole drilled to fit the thermocouple. Data were sampled 20 times every second.

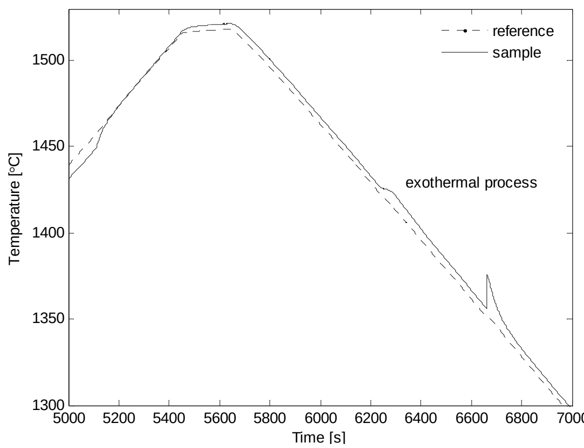

Figure 1: Temperature vs. time curve (DTA)

2.2.2 "In-situ" solidified hot tensile tests

The high temperature parameter known as the transition temperature from ductile- to brittle fracture, T_{DB} can be used as indicator if a metal is crack sensitive. In the study on crack formation during solidification of liquid metal this is a technique to find proper material data for further mathematical modelling. This temperature is measured during solidification and cooling of the metal and correspond to the point when the metal start to have a brittle mechanical behaviour. At temperatures below the transition we find plastic behaviour with necking and ability to high elongation and strains leading to ductile fractures. Low transition temperatures, below the metal solidus temperature indicate crack sensitivity.

This specific temperature can be measured by high temperature tensile testing of in-situ solidified samples. The technique is from the beginning used in the work of Rogberg and Fredriksson, and additionally developed by Karin Hansson.[7] The concept is to have a mirror furnace, which can be inserted into a tensile testing machine. The mirror furnace gives a limited heating zone by its focus, which makes it possible to melt a small part of the sample and let it solidify and cool to the tensile test temperature. This technique has the advantage that one can melt the sample and let it solidify with a controlled cooling rate which can simulate the real conditions in the casting process with regards to cooling rate, microsegregation etc.. The mirror furnace consists of three gold plated ellipsoidal reflectors with a halogen lamp inserted at the focal point. Using a maximum power of 1020 W and the centre of the test specimen placed in focal point a 5mm long melting zone was formed and held in place by the surface tension. The temperature was measured with thermocouples of type S made of Pt-Pt10%Rh placed in the centre of the melting zone. A quartz tube with argon atmosphere is placed around the specimen to protect it from oxidation. The reflectors and tensile rods were water-cooled. Elongation is measured by an extensometer. Force is measured with a load cell of 5kN in a range of ± 2.5kN. Force, position of the piston, elongation and temperature is sampled by the computer controlling the tensile test machine. Tensile specimens of 40 mm length and 4 mm diameter were heated up to T_L+5° and then cooled down with a constant rate of 2°C/s. When reaching the tensile test temperature the tensile test is performed during isothermal conditions with a constant pulling rate of 0.5mm/s which corresponds to a strain rate of 0.1/s if we assume the deformation zone to be of the same length as the heated zone i.e. 5mm.

Results from tensile tests are analyzed by the reduction of area (RA), ultimate tensile stress (σ_b), elongation (lvdt) and strain to fracture (ε). The fracture surface with zero ductility is used as indication of transition between ductile and brittle fracture. The corresponding temperature is the transition temperature, T_{DB}.

$$RA = \frac{A_0 - A_1}{A_0} \cdot 100\%$$ (A₁ is a mean value over three measurements)

$$\sigma_b = \frac{F_{max}}{A_0}$$

$$\varepsilon = \ln\left(\frac{l_0 + \Delta l}{l_0}\right)$$

2.3 Macrosegregation study

Macrosegregation occurs during solidification due to relative movement or flow of segregated liquid and solid. There are numerous causes of fluid flow and solid movement in casting processes. One reason for this movement of segregated liquid may be density differences of the metal due to temperature or variations in composition. The hot liquid metal becomes cooler close to the chill surfaces and its density increase causing downward movement. Liquid being enriched by rejected solutes with higher density compared to the bulk composition will flow downward and the opposite will happen when low mass elements enrich the liquid. During ingot casting, the most common macrosegregations are the positive, negative and channel segregations[8,9]. *Positive segregation* means that the concentration of alloying element exceeds the average bulk concentration. *Negative segregation* is instead a local lack of alloying element. The positive segregation is often found at the top and is the result of segregated liquid flow toward the top,[10,11] and the negative zone with more pure material at the bottom of the ingot is explained by sedimentation of equiaxed crystals formed in the bulk liquid.[12] Approximate at one third from the surface the so-called A-segregates are found. They have the shape of pencil-like channels, filled with alloy which contains high concentrations of the alloying elements. Liquid jet streams melt the dendrite network allowing for channels to form and be filled by enriched liquid flowing upward due to its lower density.

Drilling for chemical composition was made on ingots along the central axis and at several cross sections at different heights. The results are plotted to obtain the segregation pattern over C and S. Sulphur prints which reveal the S as dark marks are used to analyse segregation channel placement and number density. These results are used as in-data for numerical analysis.

2.4 Inclusion study

2.4.1 Inclusion characteristics

Inclusions studied in this present work were analysed with emphasis on its precipitation process and morphology. Our goal was trying to present a model on inclusion formation based on measurements on liquid supersaturation, inclusion characteristics and solidification process. Comparisons were made between different crystal morphologies such as the columnar and equiaxed crystals and metallurgical processing prior casting. Inclusions were characterized by use of scanning electron microscopy (SEM) and element concentrations are measured by electron probe micro-analysis (EPMA). From SEM images we determine type, shape and size distribution. By use of energy dispersive scanning (EDS) we analyse inclusion chemistry. EPMA results on concentration levels are used to study the precipitation process.

2.4.2 Electron Probe Micro-Analysis

Inclusions were investigated by Electron Probe Micro-Analysis, EPMA. This technique has been known since late 1950. The first instrument was in place at The Swedish Institute of Metals Research in the beginning of the 60's. An electron beam is focused to a 1 μm point by aid of electromagnetic lenses. The beam is used to penetrate the surface (2 μm deep in steel materials) influencing the atoms to enable emitted x-ray to analyse element specific wavelengths. Intensity is proportional to element amount. To enable this type of measurement some modification must be made to the original SEM equipment. Much higher, 500 – 1000 times, currents are used compared to conventional SEM and sliding sample holder render possible surface scan. Calibration for each element is made by mapping reference materials with known spectrums. One sample with low element concentration and one sample with high element concentration are used. One can choose to scan step wise in the range from 1×1 μm to 50×50 μm. The micro distribution of selected elements are traced and transformed into a two dimensional colour picture, each colour representing a certain amount. Each point represents a mean value of the element concentration. All data about references, coordinates and analyses are saved to be used for further investigation such as line-scan, mean values of certain structure areas or to better bring out low content of interesting elements.

2.5 Inoculation in nodular cast iron

The same model on precipitation process used in the study on inclusions in steel alloys can be used when evaluating the graphite formation during solidification of cast iron. Precipitation of graphite nodules during solidification in nodular cast iron was studied to better understand inoculation efficiency. Three different additives were used, FeSi – Ca, FeSi – (Ca, Ce) and FeSi – (Ca, Ce, S, O). The same mirror furnace used for hot tensile test was used to melt samples which solidify with a controlled cooling rate. The samples melt by heat conduction while heating the graphite holder to about 1400 °C. All samples were cast in Zr_2O-crucibles. A 250 mm long and 30 mm wide quartz tube is placed around the specimen set-up and was continuously filled with argon gas to protect it from oxidation. Quenching was made in water. Inoculation seeds were placed at the bottom of the crucible before melting. A total of six tests from each alloy have been studied. One from each alloy representing the total solidification interval. Five were quenched within the solidification interval (1150 – 1010 °C). Maximum heating- and cooling rate was set to 300°C and 60 °C/min respectively. Samples were kept for about one minute at the maximum temperature. Temperature was sampled every 0.4 s and measured in the centre of each sample. The time from completely liquid to start of cooling is about 100 s for all tests. A maximum temperature of about 1375 – 1360 °C has been recorded in the melt and is regarded as the inoculation temperature.

Samples were polished to a 3 um diamond paste finish and etched in 2-5% Nital, 2% Pikrin or 5%Br – 95%Methanol solution. Studies were concentrated towards microstructure, nodule count, nodule size distribution, inoculants efficiency and inclusion characteristics. Nodule count and structure fractions were made by means of point counting in 5×-magnifications. The inclusions are analysed by EDS in SEM.

3 Results

3.1 Macrosegregation

Figure 3 shows a plot over the segregation ratio, C/C_0 of carbon and sulphur in the rectangular ingot. As to be expected the macrosegregations follow the well known behaviour. In the figure, the concentration along three horizontal lines, representing three height levels, from surface to centre are shown to the left, the centreline segregation is shown in the middle and the position of each drill sample are shown to the right. A sulphur print of the corresponding surface is shown in figure 4. In this ingot, an increase of the segregation ratio is seen toward the top. The horizontal lines show that the composition are even toward the surface at the mid to lower levels but has clearly unstable segregation ratio towards the centre at the higher level, which is close to the hot-top region. This instability coincides with the A-segregates seen in the sulphur print in figure 4. At the bottom of the ingot a somewhat increasing negative segregation is found.

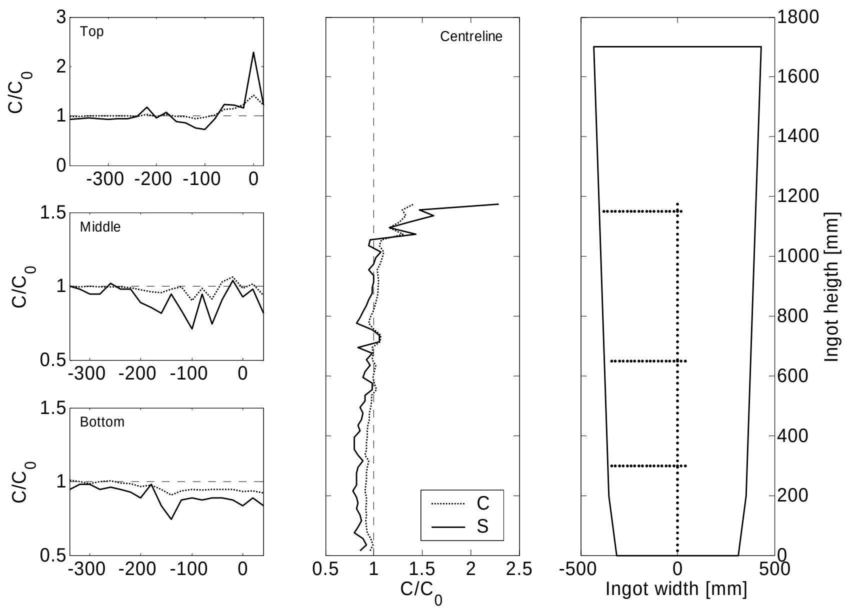

Figure 3: Segregation ratio of S and C. Sample location is shown in the right figure.

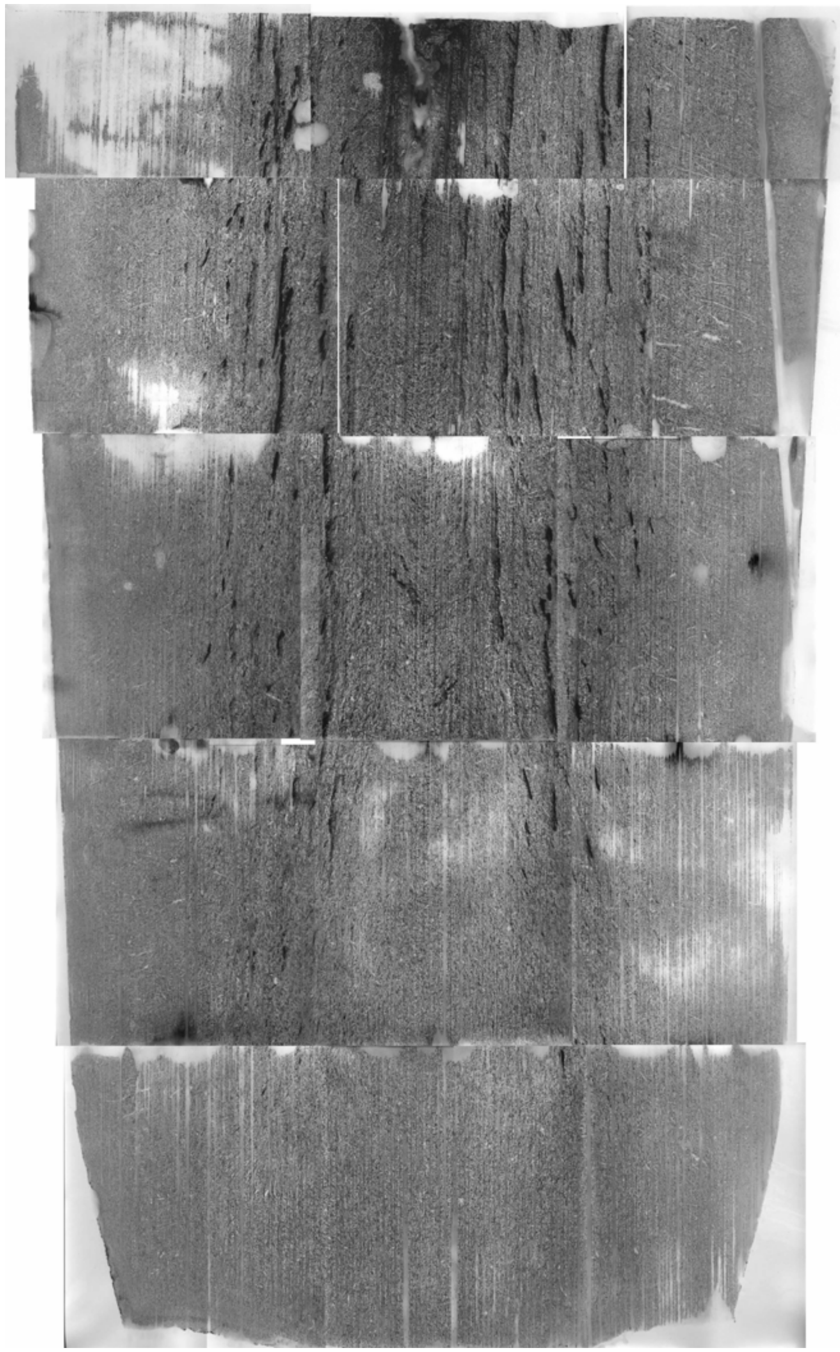

Figure 4: Sulphur print of vertical cross-section of rectangular ingot.

3.2 Inclusions characteristics

Three types of inclusions were found. To the left in figure 5 we see a duplex oxy-sulphide inclusion where MnS has grown on Al_2O_3-nucleis, the centre picture is a MnS inclusion and to the right in the figure we see the Al_2O_3. The inclusions are found in all three materials but are different in type, shape and size. MnS found in the ingots are classified as type III and I since they are sharp edged to spherical. Continuous cast material contains type II MnS which are smooth and stringy. The oxides are all faceted. Inclusion size and number density are found to be a function of crystal morphology. Columnar structure favour precipitation of MnS and duplex oxy-sulphides. Equiaxed crystal zone contains these inclusions too but to less extend together with pure Al_2O_3, most of which are very small in size.

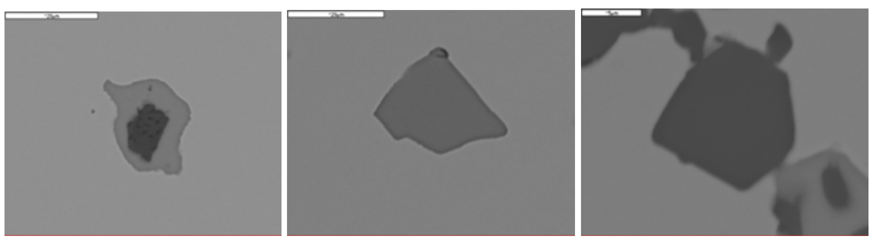

Figure 5: Duplex oxy-sulphide, pure MnS and pure Al_2O_3 in high-sulphur tool steel ingot

3.3 Inoculation in nodular cast iron

Nodule size measurements are presented in figure 6. The un-inoculated base iron samples show a low number of large nodules. The number of nodules then increase at a size of 20 – 25μm, and an additional increase is seen at a size of 5 – 10μm. Addition of Ca and S – O treated inoculants lead to a more even distribution in comparison to addition of FeSi – (Ca, Ce). FeSi – (Ca, Ce, S, O) which show a peak at 5 – 20μm is the additive with most small sized nodules.

This is explained by formation of nodules at the beginning and at the end of solidification. A support for this is found in the thermodynamic calculations [Fig 13a and 14a, supplement 3]. These show that MgO and MgS inclusions are formed at the addition of Mg and nodules are nucleated on those. MgO and MgS inclusions are also formed at the end of solidification acting as nucleation sites for graphite nodules. Addition of inoculants containing Ce or other elements with high affinity to oxygen shows a quite different nodule distribution. There is hardly any favourite size and the distribution is more even [Fig. 6, supplement 3]. This might be explained by sulphides and oxides are repeatedly formed during solidification process.

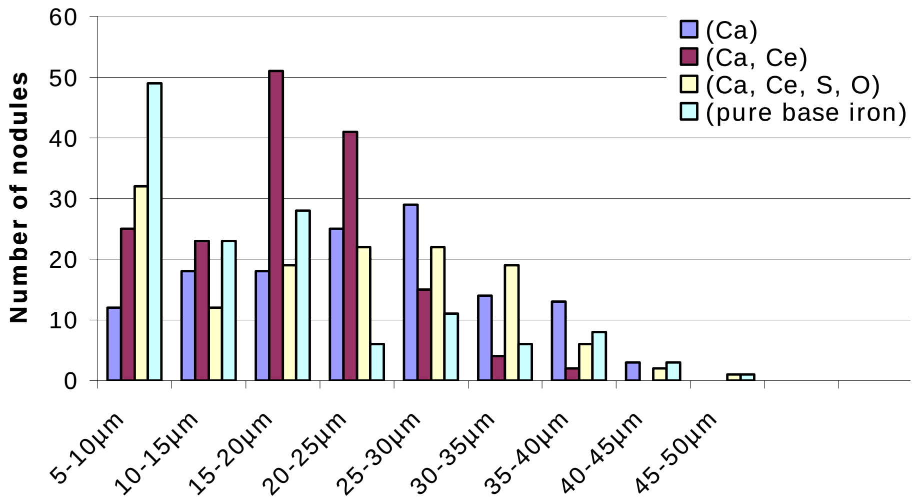

Figure 6: Nodule size distribution

4 Discussion

Results from supplement 1, 2 and 4 are to be considered as one investigation. We made different types of experiments and analyses in order to investigate the origin of defects such as segregation, crack formation and inclusions in cast ingots and continuous cast slabs. The experiments are made on the same steel quality through out the work of this thesis. Experiments were designed and tried out in order to achieve the correct material data for further mathematical modelling.

The segregation pattern in the work made in supplement 2 follows the general view on segregation behaviour. It is clear that the areas at which segregation channels are found are prone to house high number density of inclusions. This is supported by EPMA analysis over the area. The channel formation with remelting of the dendrite network causing liquid enrichment with alloy elements being pushed from the solid into the liquid with higher solubility enables the needed supersaturation to form these inclusions. Results on macrosegregation and type of inclusions has been further analysed in supplement 4 with emphasis on the inclusion formation process. The investigation shows two different types of inclusions, (1) duplex inclusion where the core constitute an oxide inclusion with a MnS outer shell and (2) pure MnS and Al_2O_3 inclusions in different morphologies. It also shows that inclusion precipitation has crystal structure dependence which is a function of solidification process. At higher solidification rates the oxides incorporate into the solid and no small nuclei are available for MnS precipitation.

The theoretical model used in supplement 3 and 4, based on well known segregation models, analyses the precipitation behaviour of inclusions during solidification process. The method to find at what point in the solidification process inclusions are expected to precipitate are based on calculations with the Scheil and Lever rule in combination with calculations on solubility products for nucleation. The theoretical results are compared with experimental observations from EPMA and microstructure investigations. The experimental result supports the calculations that Al_2O_3 inclusions precipitate before MnS and thus acting nucleation sites for MnS. Results from the structure investigation of Steel C also support this since this material contains less MnS and no oxides. This could be an effect of the metallurgical treatment prior to casting.

In the same way as for the duplex inclusions found in the steel ingots the graphite nodules precipitates on oxide nuclei. Pure base iron show uneven graphite nodule size distribution compared to the iron inoculated with S and O treated additives. When adding inoculants with Ce or elements with high affinity to oxygen the nodule size distribution change from being uneven with a low number of large nodules to a more flat distribution with hardly any favourite size. This is explained by repeatedly formed sulphides and oxides during solidification process.

5 Conclusions

Ingot casting, continuous casting and inoculation experiments has been performed with the intention to study crack formation, macrosegregation, inclusion characteristics and the effect of metallurgy and solidification process. A crack prediction model used to calculate temperature and elastic stresses was presented together with a model to calculate the influence of the A-segregates in large ingots. The formation of inclusions in steel alloys has been analysed by use of a new way to calculate the precipitation as function of supersaturation and solidification process. The same model can also be applied in the case with inoculation of cast iron.

Macrosegregation in the steel experiment in this study is similar to the general view of segregation pattern, a negative segregation zone in the lower parts of the ingot and an increasing composition toward the top. The primary source of the macrosegregation in the ingot cast material is the transport of segregated liquid in the A-segregates. These areas of saturated metal contain inclusions, mainly oxides and sulphides.

Inclusions are formed in the interdendritic areas where the liquid is highly enriched. Sulphides and oxides are the most common types together with a duplex oxy-sulphide where the MnS grow on oxide nuclei. Inclusion characteristics depend on crystal morphology which can be related to casting process. Probably this is an effect of the solidification rate, both in ingot and continuous cast processing. Calculations by aid of homogeneous nucleation theory together with segregation calculations show that precipitation of oxides start at a solid fraction of about 0.7 and the MnS not until a solid fraction of 95% is reached. Results from structure analysis support the idea that oxides act as nucleation sites for MnS precipitation. In the study on nodular cast iron it shows that oxides present in the liquid promote nodule precipitation. During solidification re-nucleation of oxides and graphite nodules result in a flat nodule size distribution with the beneficial effect of less chill i.e. less problem with micro porosity.

6 Future work

This thesis has dealt with segregation and the formation of inclusions during solidification of steel alloys and cast iron. The effects of segregation are well known and its influence on formation of inclusion is one question to answer when aiming on cleaner steel. Experiment has shown that the presence of small oxides during solidification act as nuclei for inclusion formation. The present study has aimed at classifying type of inclusion and its precipitation behaviour. MnS inclusions are found to precipitate late during solidification but oxide nuclei can be the result from metallurgical treatment prior to casting or a spontaneous formation early in the solidification process. It is most likely that metallurgical treatment is one important factor which affects the precipitation propensity. Inclusions can be less harmful in certain morphologies. One way to overcome the detrimental effect from inclusions is to control its morphology which might be governed through better understanding of the solidification process.

Spontaneously formed inclusion are considered to be detrimental to the steel quality but are treated as an asset while improving the cast structure of ductile cast iron. In both cases it is important to understand the formation parameters to be able to control the wanted effect. In cast iron graphite promoting additives might have a big impact to the solidification process. More results on precipitation behaviour as function of additive chemistry need to be analysed in order to optimise inoculation additive effect.

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