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Development of a CC mould with soft cooling properties for casting of crack sensitive steel grades
Final Report

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Sammanfattning

Projektet ”*Utveckling av stränggjutningskokill med mjukkylande egenskaper för gjutning av sprickkänsliga stål*” har bedrivits under tiden 6/12 2006 till 31 oktober 2010 inom Stålindustrins Energiforskningsprogram 2006-2010. Projektet har finansierats av Energimyndigheten med 4 miljoner kronor och av stålindustrin med 15 miljoner kronor. Forskningsutförare har varit Swerea KIMAB och deltagande företag Outokumpu Stainless Avesta Works, Sandvik Materials Technology och SSAB EMEA Luleå och Oxelösund. Jernkontoret har varit administrativ koordinator.

Den stränggjutna stålproduktionen består till stor andel av högkvalitativa stålsorter som ställer stora krav på gjuttekniken för att undvika att ytfel i varierande omfattning ska uppstå. Ytfel på stålämnena måste tas bort med slipning eller syrgashyvling vilket är energi- och kostnadskrävande och medför också att en del av ståltonnaget måste götgjutas med försämrade utbyten till följd.
Energiförbrukningen till följd av ytfel för SSAB EMEA Oxelösund, Sandvik Materials Technology (SMT) och Outokumpu Stainless i Avesta uppskattades vid projektets början till 61 GWh/år.
Målet med projektet var att utveckla ett kokillkoncept, som medger en mjukare kylning av det först bildade stålskalet, vilket minskar risken för spänningar och sprickbildning, med ambitionen att kunna halvera energiförbrukningen för ämnesytfel.
Det valda tekniska konceptet för detta ändamål var att fälla in ett värmedämpande skikt i överdelen av kopparkokillen bestående av en metall med låg värmeledningsförmåga som rostfritt stål eller nickel. Med detta koncept genomfördes projektet i fyra etapper: 1) Modellering och design av det värmedämpande skiktet. 2) Driftsförsök med en mjukkyld smalsida hos SSAB EMEA Oxelösund omfattande 9200 ton (42 charger). 3) Driftsförsök med en mjukkyld bredsida hos SMT omfattande 3 charger rostfritt stål och 3 charger kolstål. 4) Driftsförsök med en smalsida hos Outokumpu Stainless i Avesta med ett värmedämpande skikt applicerat med ”cold spray” teknik. Resultaten från projektet kan kortfattat sammanfattas enligt följande:

- Tekniken med mjukkylning i överdelen av kokillen kan reducera värmeflödet i denna del med ca. 20 % vid en tjocklek av det värmedämpande skiktet på 8-9 mm. Denna skikttjocklek resulterar i en yttemperatur på ca. 850 °C, vilket är utan risk om materialet består av värme-tåligt rostfritt stål eller nickel.
- Tekniken med mjukkyld kokill har potential att gjuta sprickkänsliga stålsorter med betydligt lägre variationer i värmeflöde genom att undvika starkt kristalliserande gjutslagger och låta den mjukkylda kokillen stå för värmedämpningen.
- Det mjukkylda skiktet kan appliceras med svetsning vilket dock innebär att nickel måste väljas som värmedämpande material beroende på höga kopparhalter i svetsen. ”Cold spray” kan vara en alternativ beläggningsteknik, men ett misslyckat försök i Avesta med denna teknik påvisade vikten av processutveckling för att skapa fungerande skikt.
- I det ursprungliga projektförslaget planerades för en implementering av tekniken på ett lämpligt stålverk. Beroende på att genomförda experiment var mer komplicerade och tidskrävande är förutsett kunde denna ambition inte genomföras av tidsskäl och bristande finansiering. För att bana väg för en snabb framtida implementering gjordes i stället en feasability study för SSAB EMEA i Luleå.
- Fortsatta aktiviteter med mjukkyld kokill föreslås att genomföras i Luleå ett fortsättningsprojekt med lågkristalliserande gjutslagger och mjukkyld kokill för gjutning av sprickkänsliga peritektiska gjutsorter. Fokus vid dessa försök kommer att vara att studera den metallurgiska effekten med avseende på ytkvalitet.

Summary

The project "*Development of a CC mould with soft cooling properties for casting of crack sensitive steel grades*" was carried out during 06/12 2006 to 31/10 2010 within the Energy Programme of the Swedish Steel Industry 2006-2010. The project got financial support from the Swedish Energy Agency, 4 million SEK, and from the steel industry, 15 million SEK. The project was carried out by Swerea KIMAB in cooperation with Outokumpu Stainless Avesta Works, Sandvik Materials Technology and SSAB EMEA in Luleå and Oxelösund. Jernkontoret was the administrative coordinator.

The Swedish continuously cast steel production consists to an increased amount of high quality steel grades. Continuous casting of special steels means an increased demand on the casting technology if extensive surface defects on the blanks should be avoided. Surface defects must be removed with scarfing or grinding which is energy and cost consuming. Also some steel grades must still be cast the ingot route because of quality reasons. The energy consumption caused by surface defects for SSAB EMEA Oxelösund, Sandvik Materials Technology (SMT) and Outokumpu Stainless AB Avesta works was estimated to be about 61 GWh/year.

The goal of the project was to develope a mould concept which allows a softer cooling of the first created steel shell resulting in blanks with better surface quality with the ambition to halve the energy costs caused by surface defects.

The chosen technical concept was to let in a thermal barrier of low conductivity material, as stainless steel or nickel, in the upper part of the mould to reduce the heat flux and by that reducing the tensions in the steel shell during the initial part of the solidification where the surface quality is created. With this concept the project was carried through with the following steps: 1) Design and modelling of the thermal barrier for a soft cooled mould. 2) Plant trials with a soft cooled narrow side mould at SSAB EMEA Oxelösund including 9200 tons (42 heats). 3) Plant trials with a soft cooled broad side mould at SMT including 3 heats of stainless steel and 3 heats of carbon steel. 4) Plant trials with a soft cooled narrow side mould with new technology for application of the soft cooled barrier with "cold spray".

The results in short were:

- The technique with soft cooling in the upper part of the mould can reduce the heat flux of about 20 % provided a thickness of the thermal barrier to be about 8-9 mm. This thickness of the thermal barrier results in a surface temperature of about 850 °C which is on the safe side if a temperature resistance stainless steel or nickel is chosen for this purpose.
- The technique with soft cooled moulds has a potential for casting of crack sensitive steel grades with much less variations in heat flux from the mould. This can be achieved by avoiding a strong crystallising mould slag, using an amorphous slag and let the soft cooling layer reduce the heat in a much more reliable way.
- The soft cooled layer can be produced with welding technique, but this require nickel as soft cooling material to avoid hot shortness which is the case for welding with stainless steel due to high levels of copper in the weld. "Cold spray" could be an alternative way to prepare the moulds for soft cooling and a test was made in Avesta which resulted in a bad surface. An investigation of the soft cooled layer led to the conclusion the technique still is promising but that there is a need for further optimisation of the cold spray process for this purpose.
- In the original plan for the project an implementation of the soft cooling mould technique on a suitable steel plant was planned. Since the experiments were more complicated and time consuming than foreseen the project time and financing was not sufficient to fulfil this ambition within the project time. In order to prepare for future implementation with a short time of accomplishment a feasibility study was made for SSAB EMEA Luleå.
- Future activities are proposed with plant trials on the broad side mould at SSAB EMEA in Luleå with the concept: soft cooled mould in combination with mould powder with low ability for crystallisation while casting crack sensitive peritectic steel grades. The focus of the project will be to study the metallurgical effect regarding surface quality.

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1. Introduction

The Swedish continuously cast steel production consists to an increased amount of high quality steel grades. Continuous casting of special steels means an increased demand on the casting technology if extensive surface defects on the blanks should be avoided which is especially valid for steel grades with a high degree of peritectic transformation, so called peritectic steels. Surface defects must be removed with scarfing or grinding which is energy and cost consuming. Also a number of steel grades have to be ingot cast of quality reasons which result in higher energy consumption due to lower yield.

The energy consumtion due to surface defects has been calculated to be 61 GWh for the companies SSAB EMEA Oxelösund, Sandvik Materials Technology (SMT) and Outokumpu Stainless Avest works.

In order to find ways for quality improvements an extensive literature study was made within the frame of the member program at Swerea KIMAB 2004 [ref. 1] which gave the following guidance regarding the problem with surface defects and how to find new ways to solve the problem:

<u>Material technical conclusions</u>

- The peritectic transformation results in a maximum shrinkage of 0.5 volume %. This in combination with a four time stronger shell, due to the phase transformation, results in a very uneven shell formation which is illustrated in Figure 1 for a peritectic stainless steel.
- The phenomen is further amplified while a small shrinkage increase the gas gap between steel shell and mould which creates a large difference in heat flux from shell to mould.
- A reduction of solidification rate reduces the rate of the peritectic reaction, thus also the tensions, which is the cause of uneven shell formation and surface cracks.

<u>Process technical conclusions</u>

- For steel grades with a high degree of peritectic transformation the solidification rate is too large especially in the meniscus region.
- There is a great need to be able to reduce the solidification rate for these steel grades but also in a way that the soft cooling effect can be regulated in an optimum way adapted to the different steel grades that will be cast.
- The only wide spread technique today to decrease the solidification rate is by using crystallising heat damping mould slags.

The use of crystallising mould slags though have a large disadvantage. In Figure 2 an idealised picture of the mould slag performance in a slab mould is shown. In reality the development of a crystallised slag layer is very ununiform during the casting. This is shown in Figure 3 from a study with billet casting [ref. 2], where the casting was drastically stopped and the mould cut in halves to be able to study the steel surface in the mould. Recently the same problem has been reported for slab casting of carbon steels at Corus UK [ref. 3]. Apart from an uneven cooling it changes during the casting which is clearly shown from the experiment made at SMT with a high basicity slag at SMT (Figure 47). Another problem with crystallising slags is that they have an upper limit. If the crystallisation rate becomes too high the mould slag will loose its lubricating properties and the slag layer can crack and fall off leading to strong variations in the heat flux. This is shown in Figure 4 [ref. 4] from measurements with thermocouples at two positions 229 mm from mould top for a casting with a mould powder with a basicity of 1.62.

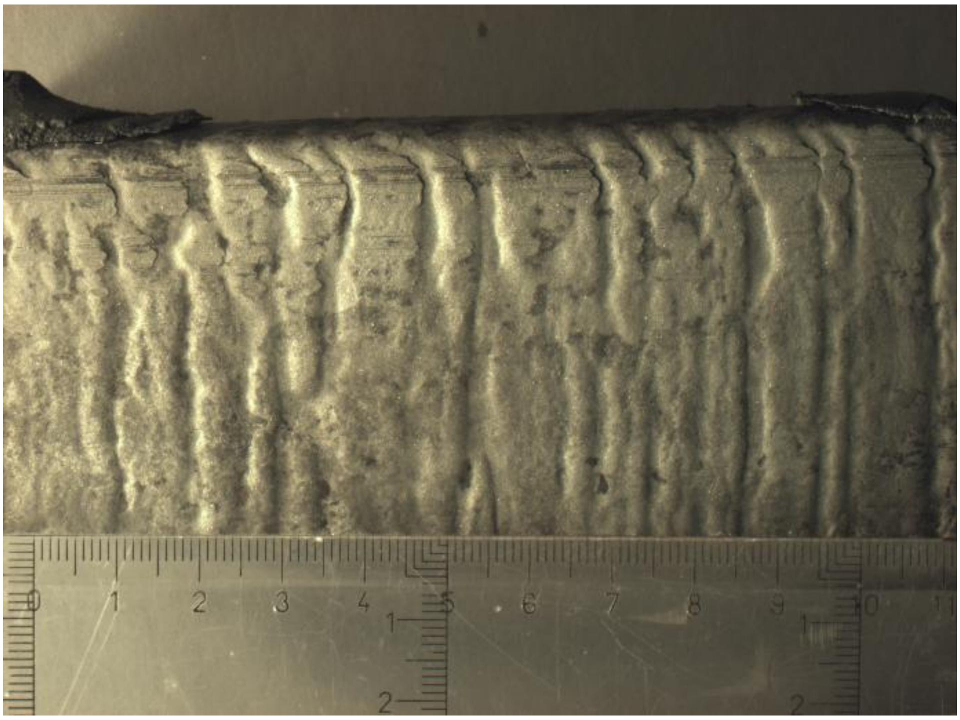

Figure 1. Example of uneven shell formation for a peritectic stainless steel grade

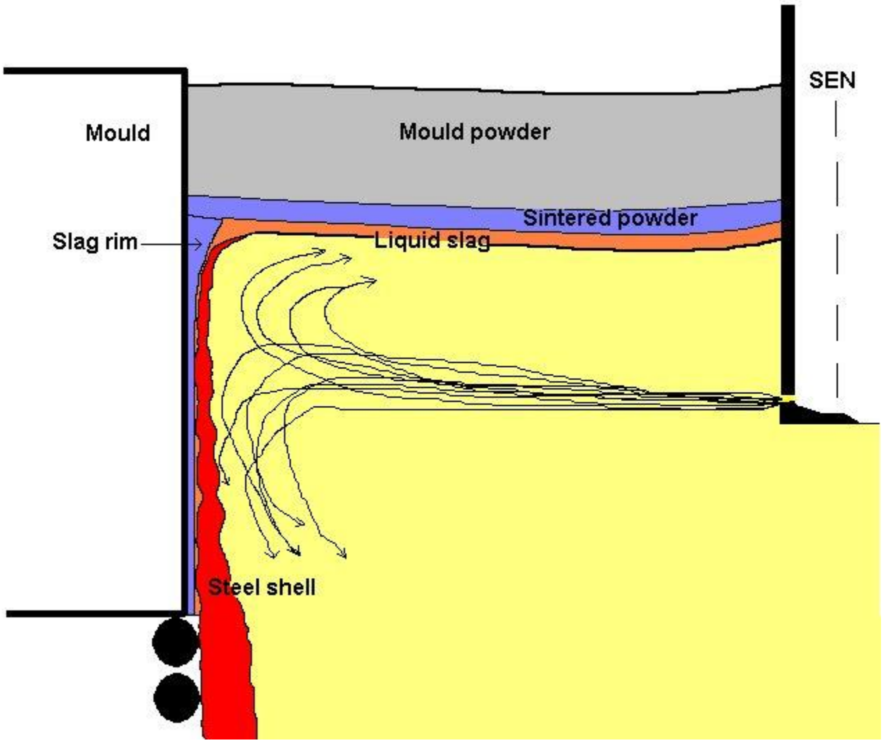

Figure 2. Schematic picture of CC mould for a slabs machine (half width).

Figure 3. Photo from billet surface with uneven mould slag coverage.

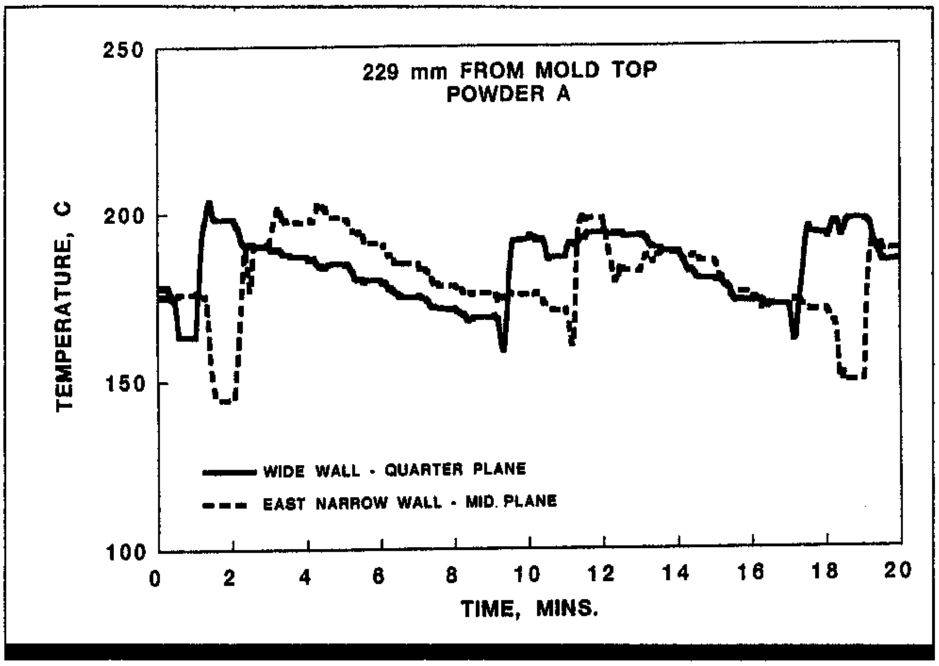

Figure 4. Temperature measurements in mould for a casting with a 1.62 basicity mould powder.

The vision for the project was therefore to develop and introduce a new type of mould where the thermal transfer could be reduced without the need of crystallising mould fluxes. By that the damping of heat flux will be done in a controlled way, thus leading to a calmer solidification with less tensions during shell formation and reduced risk of surface crack formation.

The goals of the project were the follwing:

- Develop a mould concept which allows a “soft cooling”of the first formed steel shell.
- Develop a mould concept where the soft cooling effect can be regulated or shut off.
- Develop a process technology where the soft cooled mould could be used in an optimum way with the aim to reduce the surface crack problem by half, thus reduce the energy consumption caused by this problem with 30 GWh per year when the technology is fully implemented on all three steel plants.

The technical solution which was chosen for the project is illustrated in Figure 5 and is based on the idea to set in a material with a low conductivity in the upper part of the mould. For steel grades, as peritectic grades, where a soft cooling is preferred the casting is made on a high level, for casting where a normal strong cooling is preferred the casting is made below the soft cooled layer.

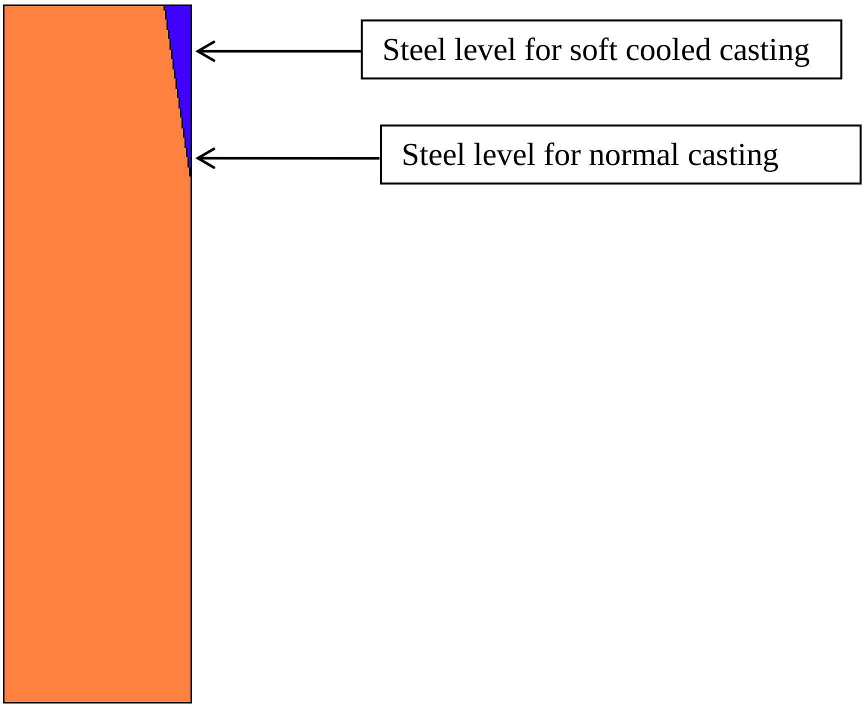

Figure 5. Schematic drawing of the soft cooled mould concept.

Because of the great risk of manipulation in the upper mould area with a heat flux of about 3 MW/m^2 the project plan was to make the development in small steps:

1. Design and modelling of soft cooled mould.
2. Experiments with instrumented mould on a narrow side mould.
3. Experiments with a broad side mould.
4. Experiments with a mould at two levels
5. Implementation of the soft cooled concept on the most suitable steel plant.

The development was made in cooperation with four steel producing companies where full scale trials were performed at three of them, SSAB EMEA Oxelösund, Sandvik Materials Technology (SMT) and Outokumpu Stainless AB in Avesta. Because of the very large experimental focus of the project a full engagement was needed from the industrial participants which is proofed by the vast number of project meetings within the project. Totally 27 project meetings were held from 6/12 2006 to 4/10 2010 whereof 12 physical meetings and 15 telephone meetings which probably is a record for the research program organised by Jernkontoret, the Swedish Steel Producers Association.

2. Design of a soft cooled mould based on modelling activities

In the meniscus area the heat flux can be as high as 3 MW/ m^2 according to Figure 6 [ref. 5].

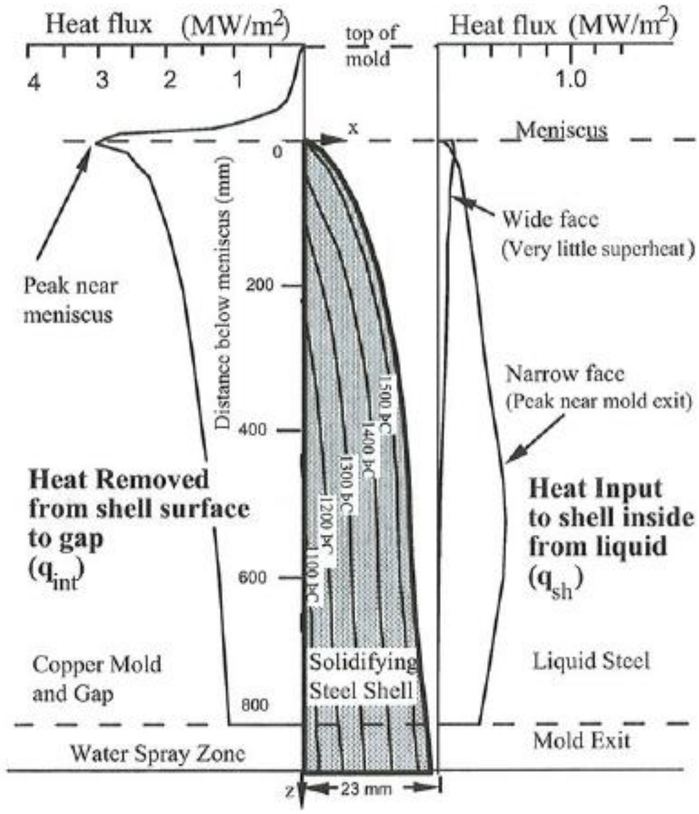

Figure 6. Heat removal from shell surface to mould [ref. 5].

So there was with a great respect the approach to make changes in the mould in this area were made. Therefore the first phase of the project was dedicated to the following activities:

- Selection of suitable material for the soft cooled wedge.
- Modelling and calculation of the wedge thickness to achieve a damping of the heat flux by 20 %.
- Modelling and calculation of stresses in the soft cooled wedge.

For a detailed description of that work a reading of the separate report of this activity is recommended [ref. 6]. In this final report only a brief summary is made.

2.1 Selection of suitable material for the soft cooled wedge

The specification of requirements for the soft cooled wedge is the following:

- High temperature (about 800 °C) for a long period. A mould campaign in Oxelösund lasts for about 2250 hours including 10 millings.
- Non oxidizing environment thanks to the carbon content of the mould powder.
- Low wear because of the soft steel shell at this position of the mould.
- Large thermal tensions due to great thermal difference between the soft cooled wedge and the copper mould.

The problem was discussed with Swerea KIMAB's specialists of high temperature materials and two stainless steel materials were chosen to be possible for the further studies: A ferritic steel grade, Kanthal APM or an austenitic 253 MA with compositions given in Table 1.

Table 1. Typical chemical composition of APM and 253 MA.

Steel grade	C	Si	Mn	Cr	Ni	Al	N	Ce
APM	0.08*	0.7*	0.4*	22	-	5.8	-	-
253 MA	0.09*	1.6	-	21	11	-	0.17	0.1

* Max

The thermal conductivity of these steels at room temperature is shown in Table 2 together with information regarding mould copper thus showing the large difference between these materials.

Table 2. Thermal conductivity at room temperature for APM, 253MA and mould copper.

Material	APM	253MA	Mould copper
Thermal conductivity,W/m, K	11	15	377

Primarily because it was difficult to find welding material for APM, 253 MA was chosen to be the wedge material.

2.2 Modelling and calculation of the wedge thickness to achieve a damping of heat flux of 25 %.

With the soft ware platform COMSOL Multiphysics calculations were made to investigate the necessary thickness of the wedge for a 20 % reduction of the heat flux, which the project committee thought was a reasonable level to aim for. It was also possible to calculate the temperature distribution in the wedge and by that its surface temperature. The calculation gave the following answers:

- The wedge should have a thickness of about 8.5 mm.
- The surface temperature for such a wedge with 253 MA would be about 850 °C which is far from the recommended service temperature of 1100 °C.

In Figure 7 a comparison is made of the temperature distribution from an ordinary mould and a mould with a 8 mm wedge made of 253 MA.

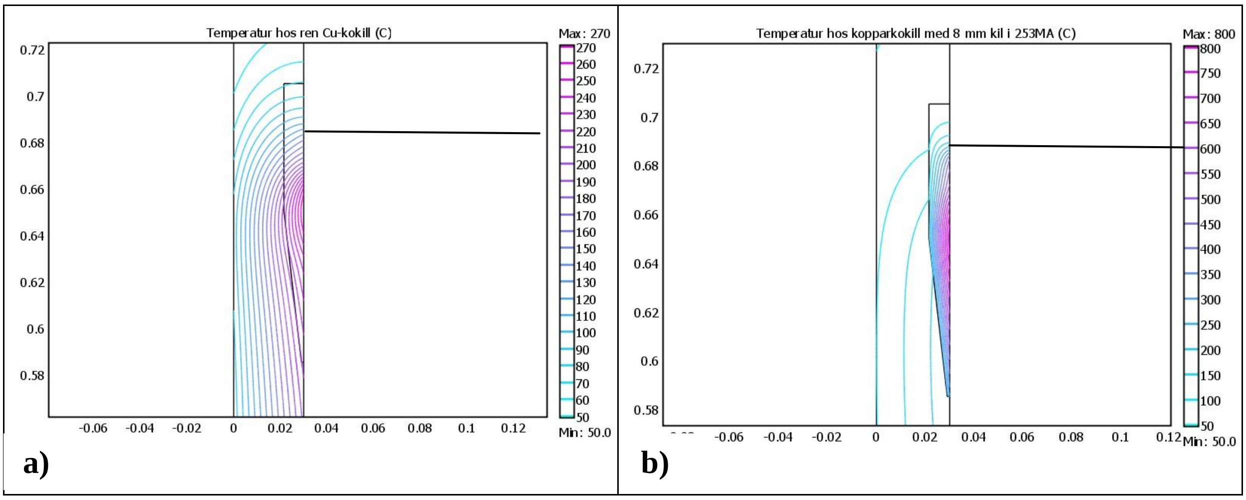

Figure 7. Temperature distribution in a mould without (a) and with (b) a 8 mm wedge of 253 MA.

Apart from the great differences in thermal distribution it should be noticed that the maximum temperature in the mould surface is not situated in the steel meniscus but about 40 mm below that due to the cooling of the upper part of the mould, which is not in contact with the steel.

2.3 Modelling and calculation of the soft cooled wedge

Although the chosen material had sufficient properties to withstand the high surface temperatures, there was a fear that laminations would appear in the binding between the copper and wedge due to strong thermal tensions. Therefore calculations were made with the soft ware DEFORM to investigate this issue which gave the following results in short:

- The tensions in the region close to the copper mould are small.
- A small plastic deformation could be expected in the surface.
- The surface deformation is smaller for 253 MA compared to APM.
- The surface deformation is reduced with increasing wedge thickness.

3. Results from experimental work at SSAB EMEA in Oxelösund

Based on the preparatory design and modelling work the first experiment was chosen to be on a narrow side mould at SSAB EMEA in Oxelösund [ref. 7]. As suggested the steel wedge should be 8.5 mm in thickness at its thickest part consisting of 253 MA where the other dimensions are shown in Figure 26. The welding should be done by the maintenance department in Oxelösund which had equipment and a long time experience of copper welding. The trial was made with instrumented moulds both of the soft cooled mould and the other narrow side mould which acted as reference mould. As a total 12 thermocouples [T.C.] were installed on each mould which is shown in Figure 8.

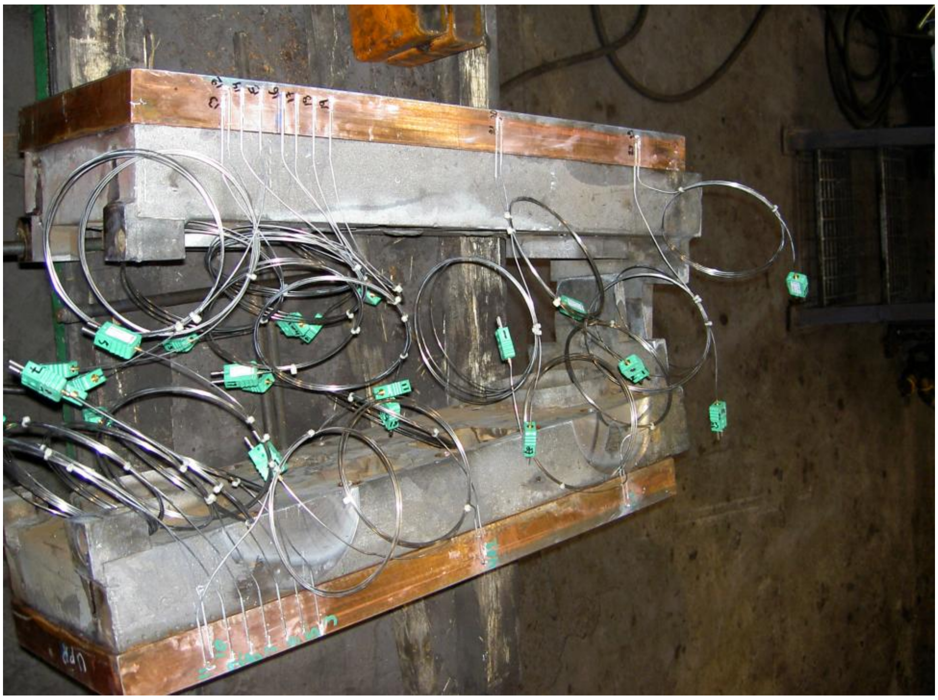

Figure 8. Photo of mould instrumentation for the experiments at SSAB EMEA in Oxelösund.

The experiment had two goals:

- Long time trial making it possible to study the effect on the stainless steel wedge.
- Make a detailed investigation of the process performance of the first four heats which were cast with four different steel grades with varying degree of peritectic transformation.

3.1 Results from long time trials

After the first four heats starting in November 2007, that was thoroughly investigated with data logging of the T.C:s, the mould was used in normal operation without particular investigations. The surface of the soft cooled layer became more and more rough but was still OK for normal service. After 46 heats corresponding to 9200 tons of steel and 53 hours of casting time, the soft cooled mould was taken out of operation and sent to Swerea KIMAB for investigation. The results from this investigation are described in chapter 5.

3.2 Results from process evaluation of the first four heats

3.2.1 Steel composition

The steel compositions of the four heats that were followed-up in detail are shown in Table 3.

Table 3. Chemical composition of the test heats, wt-%.

Charge	Grade	C	Si	Mn	P	S	Cr	V	Ti	Al	Nb	B
46173	744	0.13	.49	1.24	.011	.002	0.63	.010	.017	.045	.018	.001
46174	538	0.16	.23	1.40	.013	.001	0.23	.019	.004	.059	.015	.001
46175	526	0.17	.21	1.41	.010	.001	0.25	.019	.003	.056	.016	.001
46176	530	0.18	.20	1.38	.012	.001	0.24	.008	.005	.060	.013	.002

The carbon equivalent and calculation of Ferrite Potential according to Wolf [ref. 8] is shown in Table 4.

Table 4. Calculated carbon equivalent and FP.

Charge	C_P	FP
46173	0.084	1.040
46174	0.134	0.915
46175	0.148	0.881
46176	0.154	0.864

The rate of peritectic transformation is at its maximum for FP = 1 which is almost the case for heat no 46173 from where an IDS-analysis is shown in Figure 9. From this analysis it appears that the peritectic reaction takes place over a very narrow temperature range (1475 °C to 1446.5 °C).

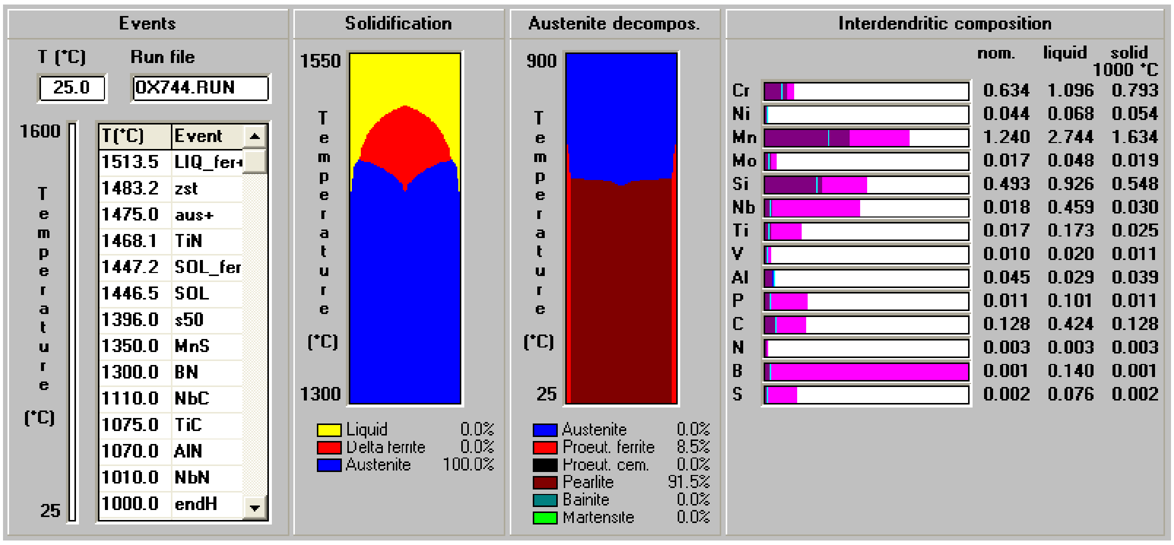

Figure 9. Result from IDS-calculation of steel from heat no. 46173.

3.2.2 Mould slag composition

Important physical data for the mould powder is shown in Table 5 from a calculation of mould slag composition based on information from the manufacturer. From the composition theoretical calculations have been made to achieve information regarding the properties of the mould slags where the calculation of NBO/T (Non Bridging Oxygen/Tetraeder) is made with a formula from a book written by Ken Mills [ref. 9]. Cuspidine is the most common crystal type for these slag systems and the theoretical calculation is a pure stoichiometric calculation for the bonding of cuspidine with the formula $3CaO{\cdot}2SiO_2{\cdot}CaF_2$.

Table 5. Important physical data for mould slag collected from the mould.

Basicity (CaO/SiO_2)	1.03
Basicity(($CaO+MgO/SiO_2+Al_2O_3$)	0.90
NBO/T	1.61
Theoretical cuspidine content, %	58

The measurement of viscosity and break temperature based on the viscosity measurement was made in Oxelösund with the result shown in Table 6.

Table 6. Measured viscosity and break temperature.

Viscosity$_{1300\ °C}$, Poise	3.5
Break temperature, °C	1220

Conclusions:

- The basicity is at a medium rate, calculated from the mould powder which it is 1.03.
- Due to a high amount of fluorine the theoretical cuspidine content is high, 58 %, which means that the crystallinity of the slag will be high, which also is seen from the measured break temperature.

3.2.3 Summary from temperature measurements

In Figure 10 the mean temperatures are shown from heat no. 46173.

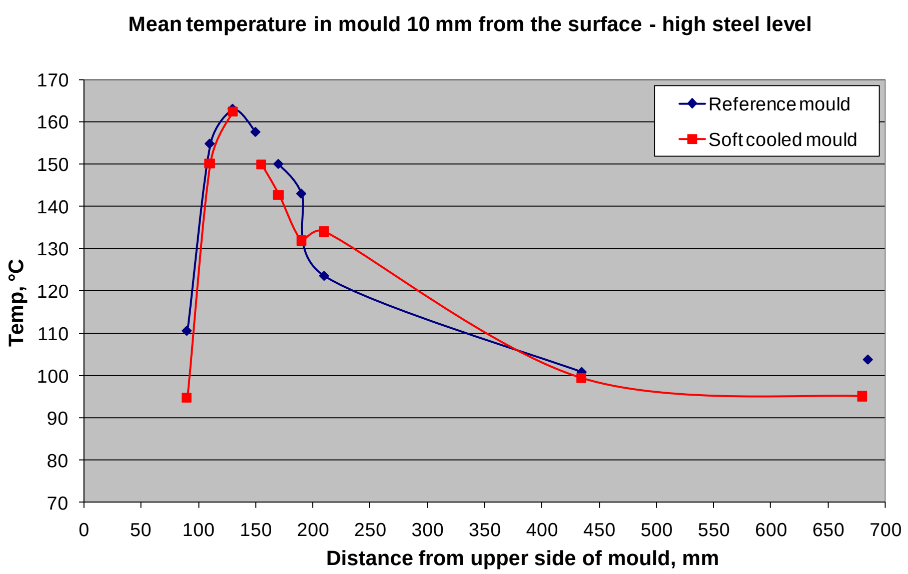

Figure 10. Mean temperature for heat 46173.

Conclusions:

- The temperature is lower at the position of the stainless steel wedge because of the heat barrier.
- At the position directly below the wedge the temperature will become about 10 degrees higher for the soft cooled mould because of the thinner and hotter steel shell.
- Further down the mould this temperature difference will be levelled out and at the end of the mould the temperature is even lower probably because of better contact between mould and shell.

It stands clear that the reduction in shell thickness in the upper part of the mould will be levelled out further down the mould which is also shown in Figure 11, which shows the heat flux 345 mm from steel meniscus calculated from measurements of two thermocouples 10 and 20 mm from the surface.

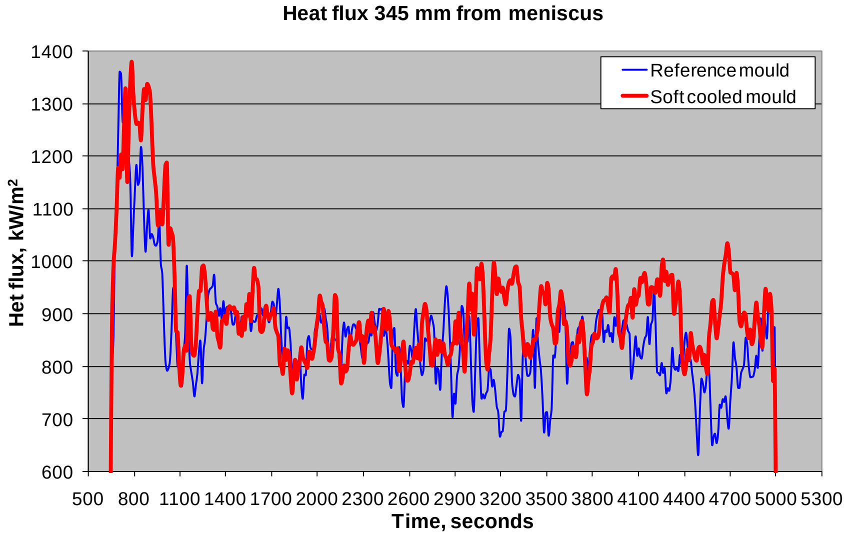

Figure 11. Heat flux 345 mm from meniscus for heat 46173.

3.3.3 Calculations of the wedge influence on the local heat flux

Based on the mean temperatures exemplified in Figure 10 calculations were made with COMSOL Multiphysics which is exemplified in Figure 12.

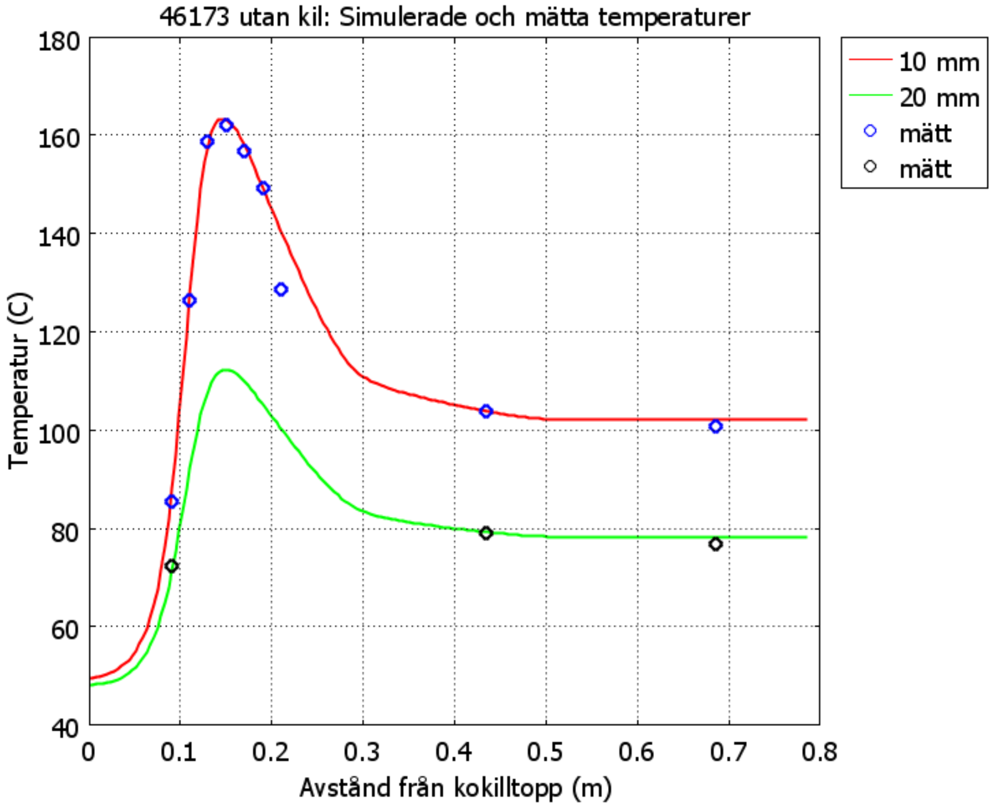

Figure 12. Measured and calculated temperatures for heat 46173.

Based on the calculation in Figure 12 it was possible to calculate the heat flux for the soft cooled reference mould and evaluate the influence of the wedge on the local heat flux in the wedge region which is presented in Table 7.

Table 7. Local heat flux with soft cooled mould and reference mould.

Heat no.	Reference mould $(10^5 \cdot W/m^2)$	Soft cooled mould $(10^5 \cdot W/m^2)$	Reduction of heat flux (%)
46173	1.62	1.45	10
46174	1.61	1.35	16
46175	1.64	1.38	16
46176	1.62	1.39	14

From the design work in chapter 2 a reduction of the heat flux of about 20 % was calculated. The reason for the measured lower values in Table 7 is the fact that the stainless steel wedge only got a thickness of 6-7 mm which is shown in Chapter 5.

3.3.4 Summary from measurements of oscillation mark depth

To be able to measure the oscillation mark depth a 2 meter long slab was taken out from each heat and cut in a longitudinal section close to the narrow sides. By this it was possible to measure the oscillation mark depth with Swerea KIMAB's laser based equipment shown in Figure 13.

Figure 13. Swerea KIMAB's equipment for measurement of oscillation mark depth.

From the measurements an evaluation of relative oscillation mark depth can be made which is exemplified in Figure 14.

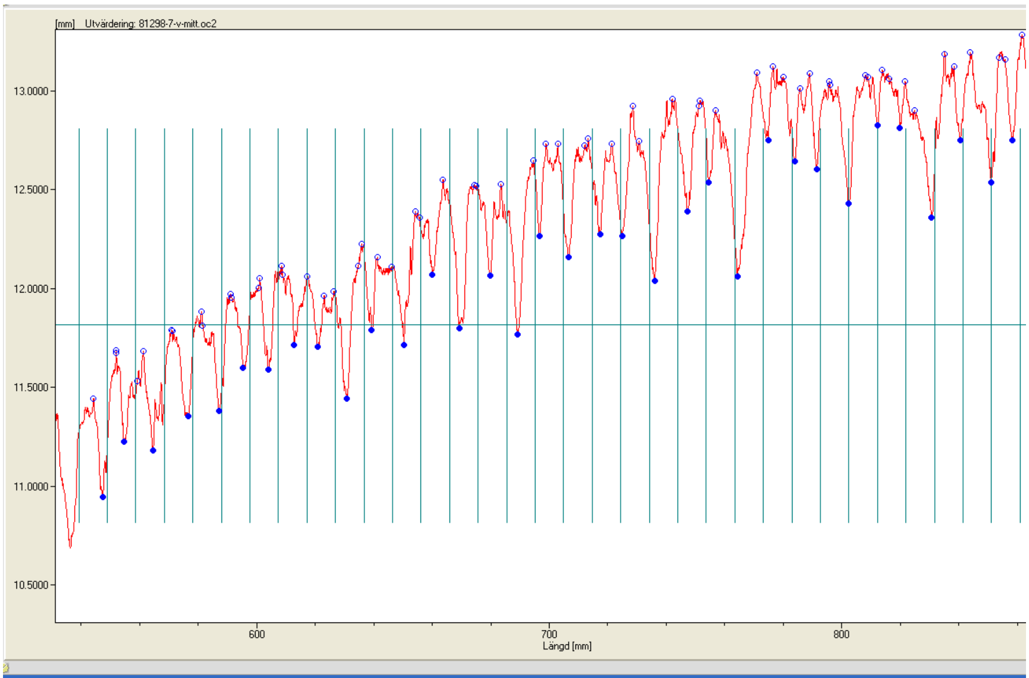

Figure 14. Surface profile with marked oscillation marks.

The results from the measurements are shown in Figures 15 and 16.

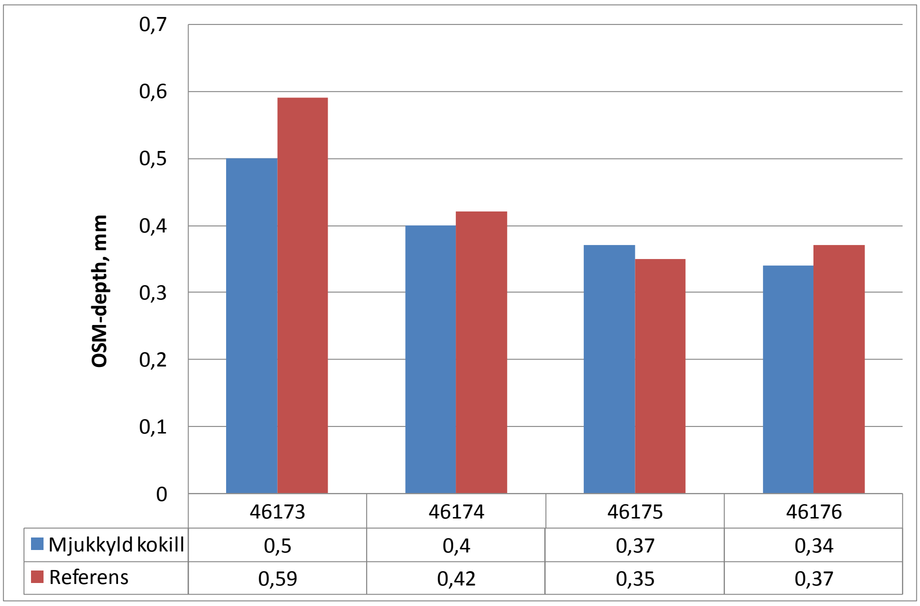

Figure 15. Results from measurements of oscillation mark depth.

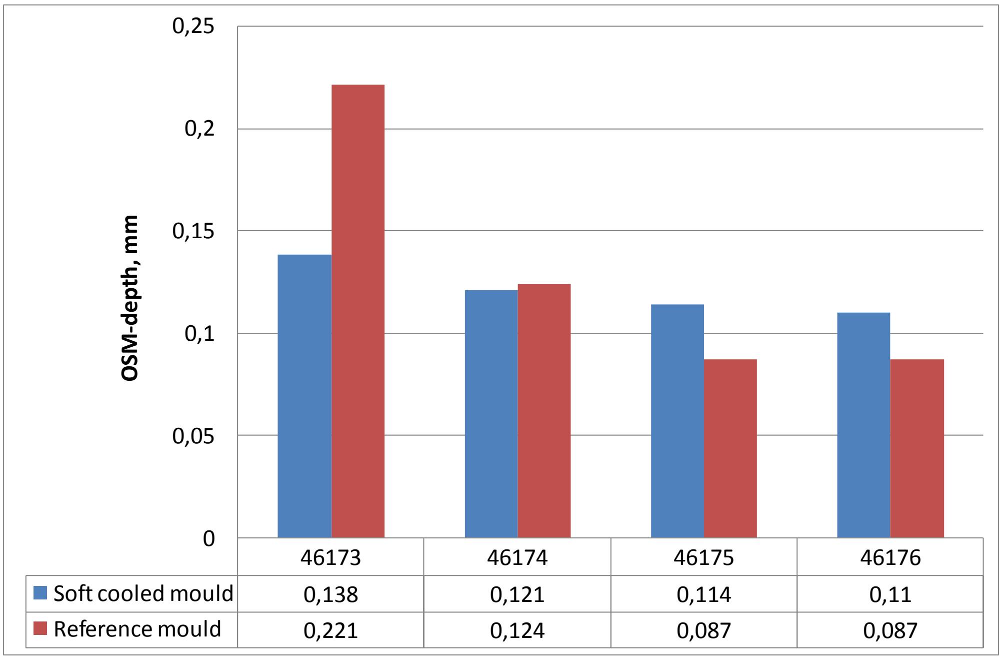

Figure 16. Standard deviation from measurements of oscillation mark depth.

Conclusions:

- Oscillation mark depth is largest for the steel grade with the lowest carbon equivalent and strongest peritectic reaction which also is reported in the literature [Ref. 10] according to Figure 17. The positive effect of the soft cooled mould is also largest for this steel grade both regarding depth and standard deviation.
- For the other heats with a higher carbon equivalent only small differences can be seen, for heat 46175 and 46176 the standard deviation is even smaller for the reference mould.

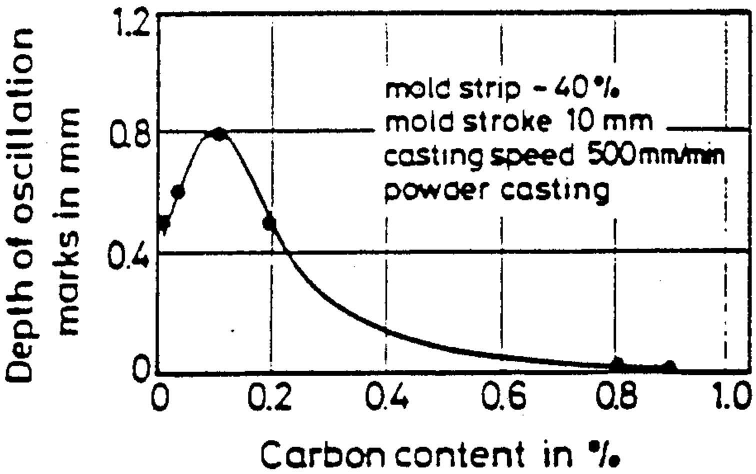

Figure 17. Oscillation mark depth as a function of carbon content [ref. 10]

4. Results from experimental work at Sandvik Materials Technology (SMT)

For broad side tests the continuous caster at Sandvik Materials Technology was chosen. When the trial was planned it stood clear that the experimental activities at SMT could not be done without the investments in a new mould. This fact in connection with the disturbance in the steel production due to the financial crisis 2009, delayed the experiments with about one year compared to the original planning. Thus the experiments were made very close to the end of the project. Therefore it was not enough time for a separate report as for the experiments in Oxelösund. That is why this final report includes such a large part from the experiments at SMT.

The continuous caster in Sandviken is a three strand bloom machine with the format 365*265mm. The machine is curved which complicates the evaluation of the experiments with soft cooling. Therefore it was decided to make the trials at SMT in two stages:

- The first with an instrumented mould without soft cooling moulds as reference in order to map the difference in mould temperatures between the fixed and loose side.
- The second stage should be made with instrumented moulds where the loose side was equipped with a soft cooling mould.

To be able to get as much information as possible from the experiments it was decided that they should be done with two different steel grades, one low alloyed steel and one stainless steel. These steels are cast with two very different mould powders. It also gave an opportunity to evaluate the influence on soft cooling together with a high basicity slag with strong tendency to crystallisation and a low basicity, glassy, mould powder. Important data regarding the mould powders for the trials according to the data sheet from the manufacturer are shown in Table 8.

Table 8. Important data regarding the mould powders for the experiments.

Used for steel grade	Stainless steel	Carbon steel
C_{free}, wt-%	4,1	17,2
Basicity (CaO/SiO_2)	1,4	0,9
$Viscosity_{1300\ °C}$, Poise	0,8	13,4

Set point chemical compositions of the two alloys are shown in Table 9**.**

Table 9. Chemical composition of steel grades for the experiment.

	C	Mn	Si	Cr	Ni	Mo	N	Al
Carbon steel	0,20	0,65	0,25	1,30	2,90	0,22	0,010	0,025
Stainless steel		1,70	0,40	16,80	11,20	2,05	0,070	

The carbon equivalent for the carbon steel is C_P = 0.41 which means that the steel will solidify in a fully austenitic way. The Ni/Cr-equivalent for the stainless steel is Ni'/Cr' = 0.63 which is an unstable alloy region. This means that the alloy will solidify with simultaneous growth of δ-Fe and γ-Fe.

These steel grades are not to be considered as crack sensitive and no surface cracks could be detected neither on the blooms cast in the strand with the soft cooled mould nor from the other strands.

4.1 Mould instrumentation

With experience gained from the experiments with instrumented mould at SSAB EMEA in Oxelösund a new plan for the instrumentation was made for the trials at SMT. The location of the thermo couples (T.C.) was selected primarily for a possibility to make a good evaluation with the modelling aids that was developed in the beginning of the work [ref. 6] and further developed within the frame of the VINNOVA steel research programme [ref. 11]. An example of the T.C. locations for the fixed side is shown Figure 18 with the following explanations:

F1,112,5, 100, 10: Fixed side = the side placed on the fundament.
F**1**,112,5, 100, 10: T.C. number.
F1,**112,5**, 100, 10: Distance from the corner
F1,112,5, 100, **10**: Distance from the mould surface

As a total 18 T.C. were mounted in each of the fixed and the loose side mould where a summary of thermocouple locations is given in Table 10. As a total temperatures from 36 T.C:s were sampled during the trials. Because of the 8,5 mm thick wedge the installation of the upper part for the soft cooling mould had to be installed 15 mm from the mould surface according to Table 11.

Table 10. Summary of T.C. installation of the fixed side.

Location	Number	Explanation
112,5 mm from the corner and 10 mm from the mould surface	11	F1 – F11
112,5 mm from the corner and 20 mm from the mould surface	2	F12, F13
72,8 mm from the corner and 10 mm from the mould surface	5	F14 – F18

Table 11. Summary of T.C. installation of the soft cooled mould.

Location	Number	Explanation
112,5 mm from the corner and 15 mm from the mould surface	7	K1 – K7
112,5 mm from the corner and 10 mm from the mould surface	4	K8 – K11
112,5 mm from the corner and 20 mm from the mould surface	2	K12, K13
72,8 mm from the corner and 15 mm from the mould surface	5	K14 – K16
72,8 mm from the corner and 10 mm from the mould surface	2	K17 – K18

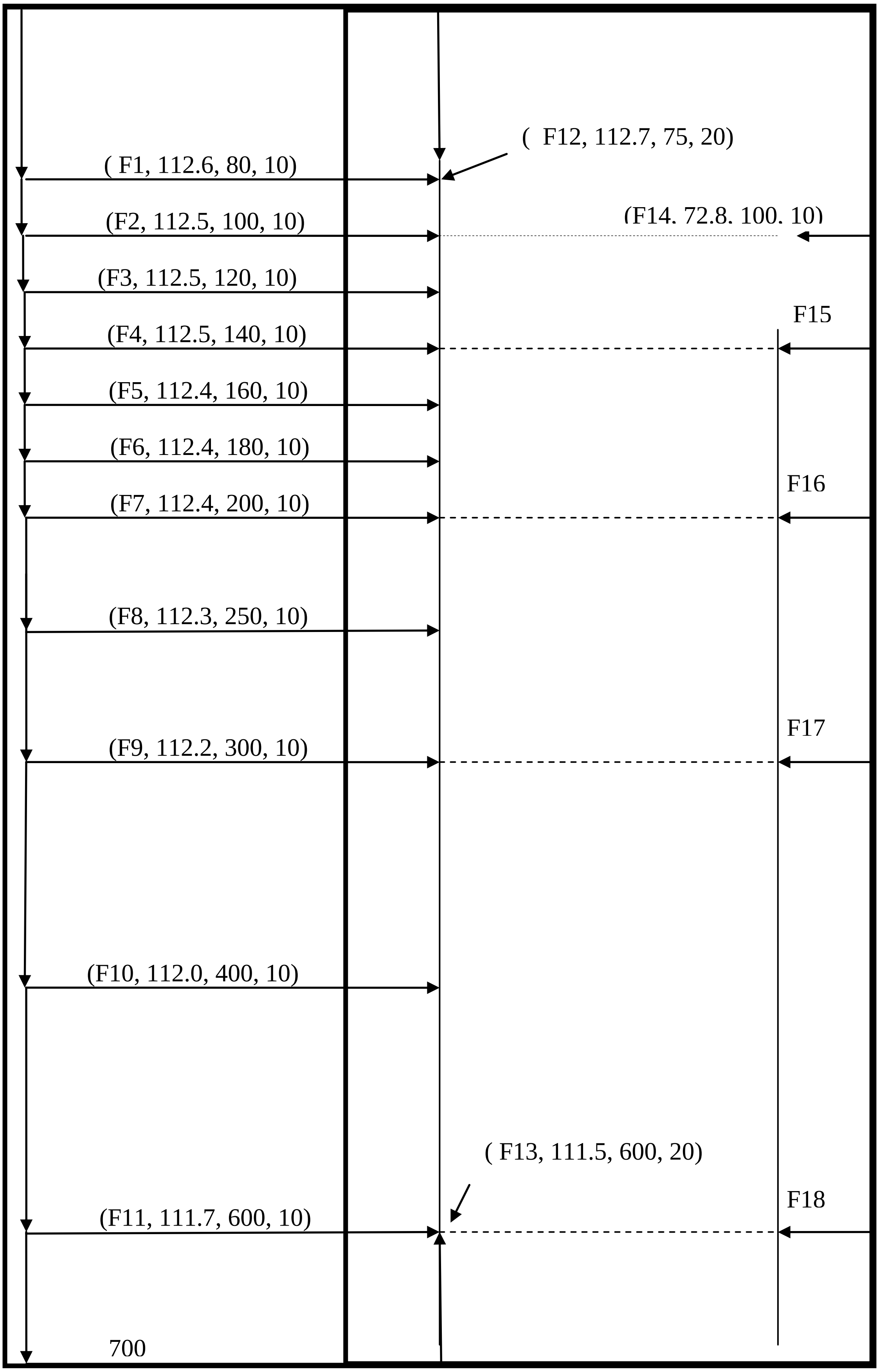

Figure 18. Location of T.C.:s for the fixed side.

It must be emphasised that the different location of the T.C. in the upper part of the fixed and soft cooled moulds made a direct comparison from the measurements impossible and detailed analysis is dependent of qualified modelling. With this it will become possible to get full information of temperature distribution in the mould and most important the heat flux at different positions.

The preparation of the T.C. installation with drilling of holes and other additional work was done at the work shop of Swerea KIMAB. The mantle T.C.:s of type K were installed by Christer Eggertsson on the mould workshop in Sandviken. Before the moulds were sent from Swerea KIMAB the distance of the T.C. holes from the copper surface were investigated with ultra sound technique in order to get the exact distance. This is necessary in order to increase the quality of the modelling work. The actual distances of the T.C.'s for the fixed and loose mould for the reference experiments are shown in Table 12.

Table 12. Exact location of TC holes.

F1	8,71	L1	8,86
F2	8,81	L2	8,51
F3	8,79	L3	8,35
F4	9,02	L4	8,67
F5	8,8	L5	8,98
F6	9,05	L6	8,77
F7	8,72	L7	9,17
F8	8,6	L8	9,13
F9	9,18	L9	9,06
F10	8,86	L10	8,6
F11	8,54	L11	9,02
F12	18,05	L12	18,1
F13	18,14	L13	18,3
F14	8,85	L14	8,73
F15	8,7	L15	8,67
F16	8,62	L16	8,8
F17	8,89	L17	8,47
F18	9,14	L18	8,97

Two pictures from the T.C. installation are shown in Figures 18 and 19.

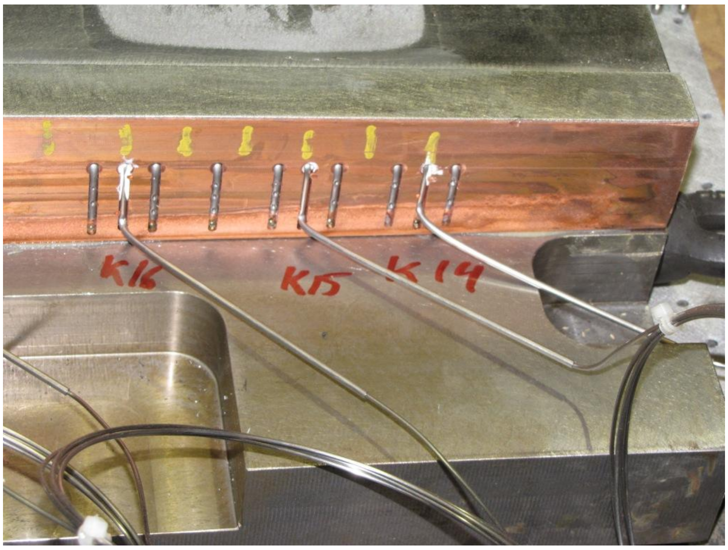

Figure 18. Installation of mantle T.C's in the soft cooled mould.

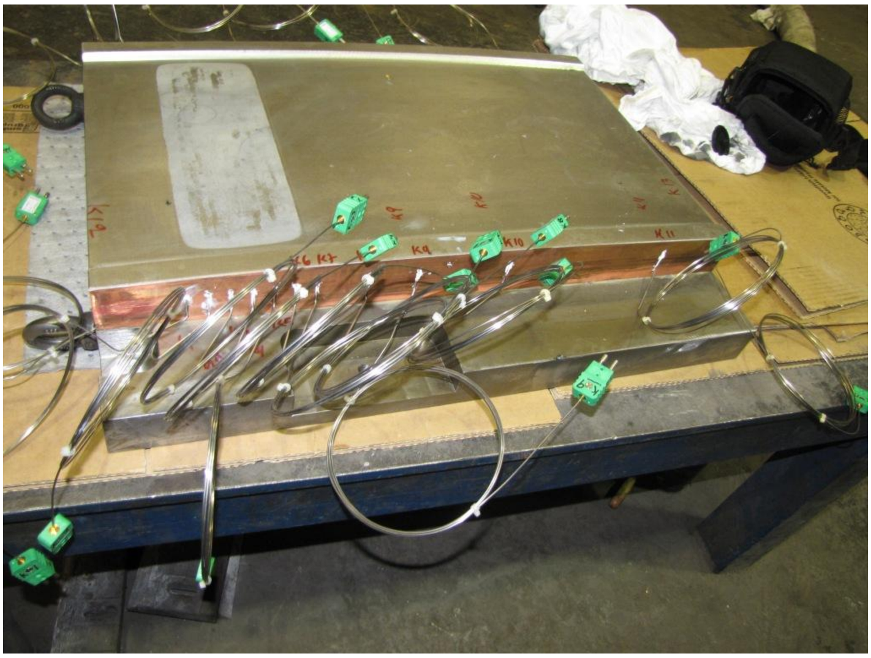

Figure 19. Soft cooled mould mantled with 18 T.C's.

4.2 Results from reference trials at Sandvik Materials Technology

The reference trials were carried out at two occasions:

- 2009-09-21. Totally 8 heats were followed up and recorded from the carbon steel grade, three single heats (523114, 523115 and 523116), one sequence with two heats (523122-523123) and one sequence with three heats (523119-523121).

- 2009-09-25. Totally 4 heats were followed up and recorded from the stainless steel grade, two sequences with two heats (523172-523173 and 523174-523175).

Some figures from the reference trials are shown in Figures 20-22.

Figure 20. Instrumented mould with T.C. cables.

Figure 21. Swerea KIMAB:s new equipment for data logging.


Figure 22. Data logging by Karin Hansson Antonsson (SMT) and Christer Eggertsson (KIMAB).

In Figure 6 the new equipment for data logging is shown which was purchased especially for the project by Swerea KIMAB which enables 40 signals (as T.C.) to be collected simultaneously at a frequency of 1 per second which was used in the experiments.

The results from these experiments were also used as validation for the project aiming at developing models for shell formation [ref. 11] which were evaluated by Ulf Sjöström at Swerea MEFOS. In Figure 23 the mean value for the temperature measurements for T.C. F1-F11 is shown. The following conclusions can be drawn from this figure:

- Very small variations for the two sequences of stainless steel.
- Larger variations for the carbon steel probably due to larger differences of steel temperature according to Table 13.

- Very large difference between carbon steel and stainless steel of the following reasons:
    - Higher steel temperature for the carbon steel.
    - Less heat flux through the mould slag for the stainless steel due to higher crystallisation rate which means thicker slag and less heat loss by radiation.
    - Lower thermal conductivity in stainless steel compared to carbon steel.

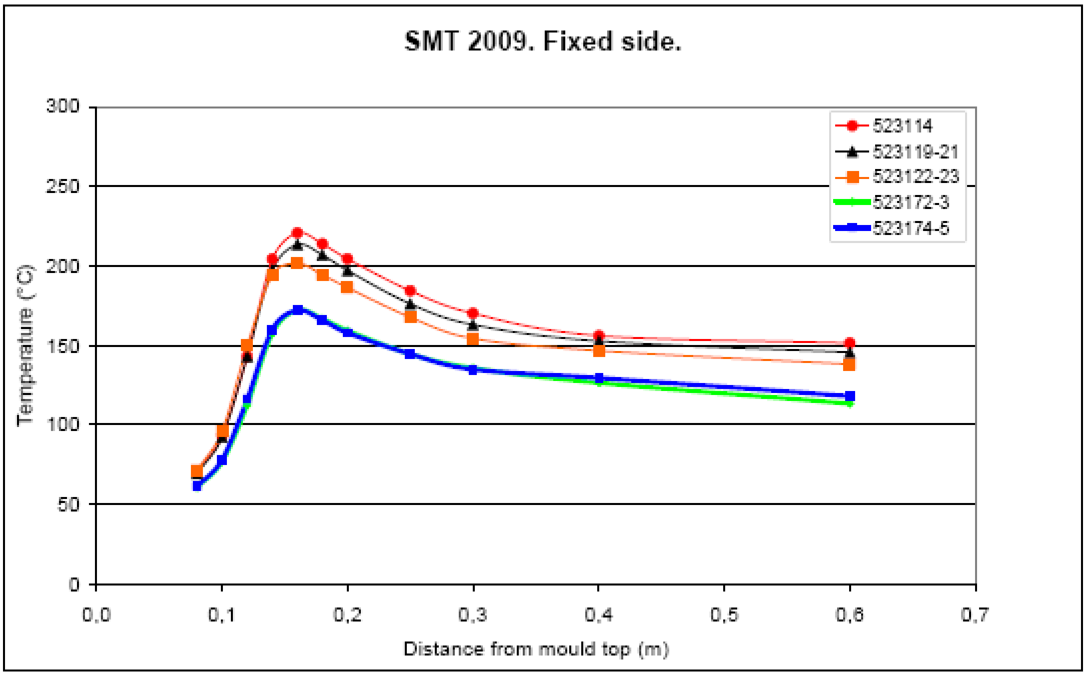

Figure 23. Mean temperatures in fixed mould for the investigated heats.

Table 13. Mean tundish temperatures for the test heats.

Heat number	**Steel grade**	**Temperature, °C**
523114	Carbon steel	1531
523119 - 5231121	" "	1543
523122 - 5231123	" "	1546
523172 - 523173	Stainless steel	1475
523174 - 523175	Stainless steel	1472

In Figures 24 and 25 a comparison is made between the mould temperatures in the fixed and loose side of the CC machine for one sequence of stainless steel and one sequence of carbon steel with the following conclusions:

- For the carbon steel there were no differences in the upper part of the mould. From 140 mm down to 400 mm there is an obvious higher temperature of the loose side. At the bottom of the mould, 600 mm from the upper side, this temperature difference has disappeared.
- For the stainless steel there were no differences down to 200 mm from the upper surface. From that position there is also an obvious higher temperature of the loose side which is levelled out at the bottom of the mould.

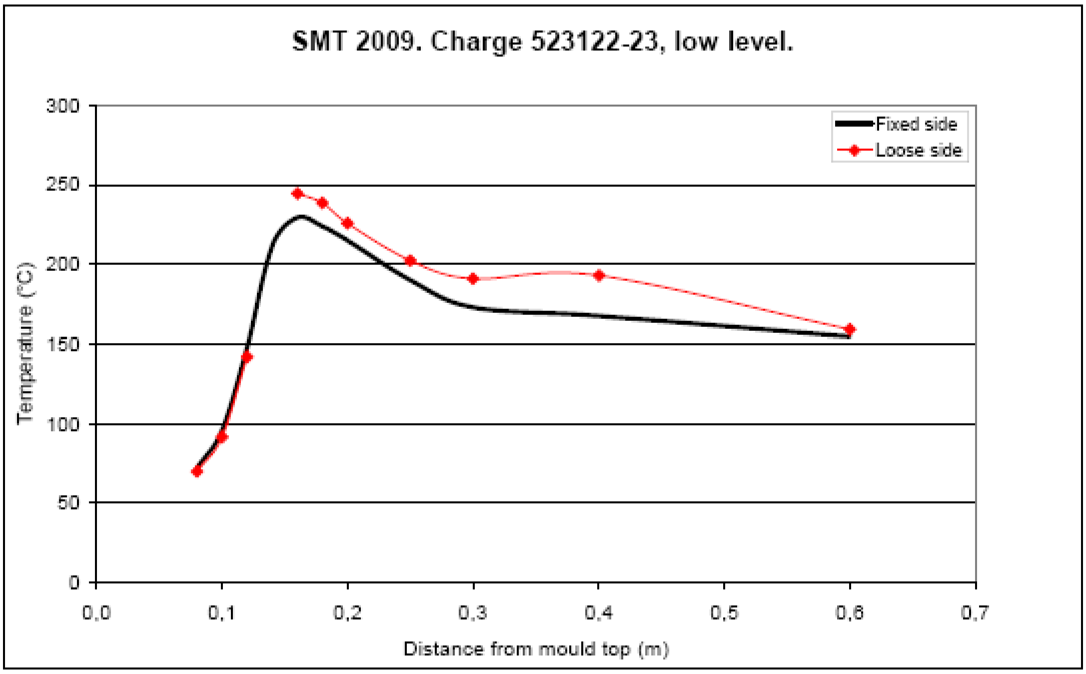

Figure 24. Mould temperatures for the carbon steel, fixed and loose side.

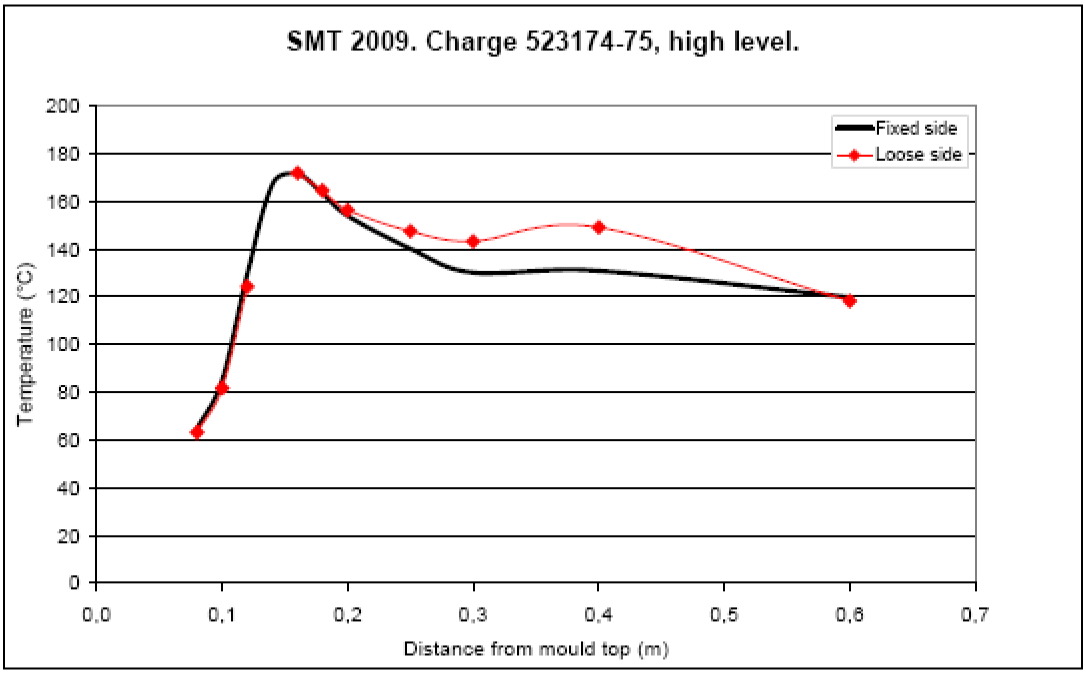

Figure 25. Mould temperatures for the stainless steel, fixed and loose side.

A summary of the reference trials is that there is a consequent temperature difference between the fixed and the loose side in the middle area of the mould. This must be accounted for when it comes to the evaluation of tests with soft cooling.

4.3 Results from trials with soft cooling at SMT

4.3.1 Mould preparation

For the trials with soft cooling at SMT the same instrumented mould for the fixed side was used as a reference mould. The mould for soft cooling was first milled for the soft cooled wedge and then sent to SSAB EMEA in Oxelösund, where the welding was made in the same way as for the soft cooled mould which was tested in Oxelösund, which is 2 mm of welding with TIG and thereafter welding with pin electrodes. Due to reasons described in chapter 5 the soft cooled material this time consisted of nickel. The dimensions of the soft cooled wedge, which was located starting 80 mm from the upper side of the mould, are shown in Figure 26. In Figures 27-29 some photographs from the preparation of the mould are shown.

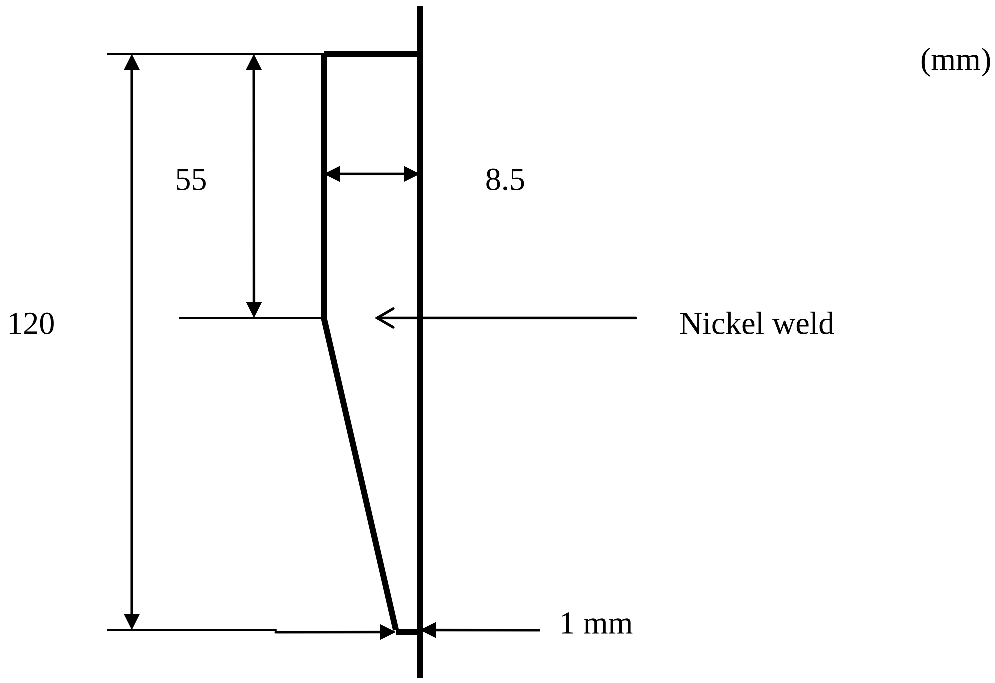

Figure 26. Dimensions of the nickel wedge for soft cooling.

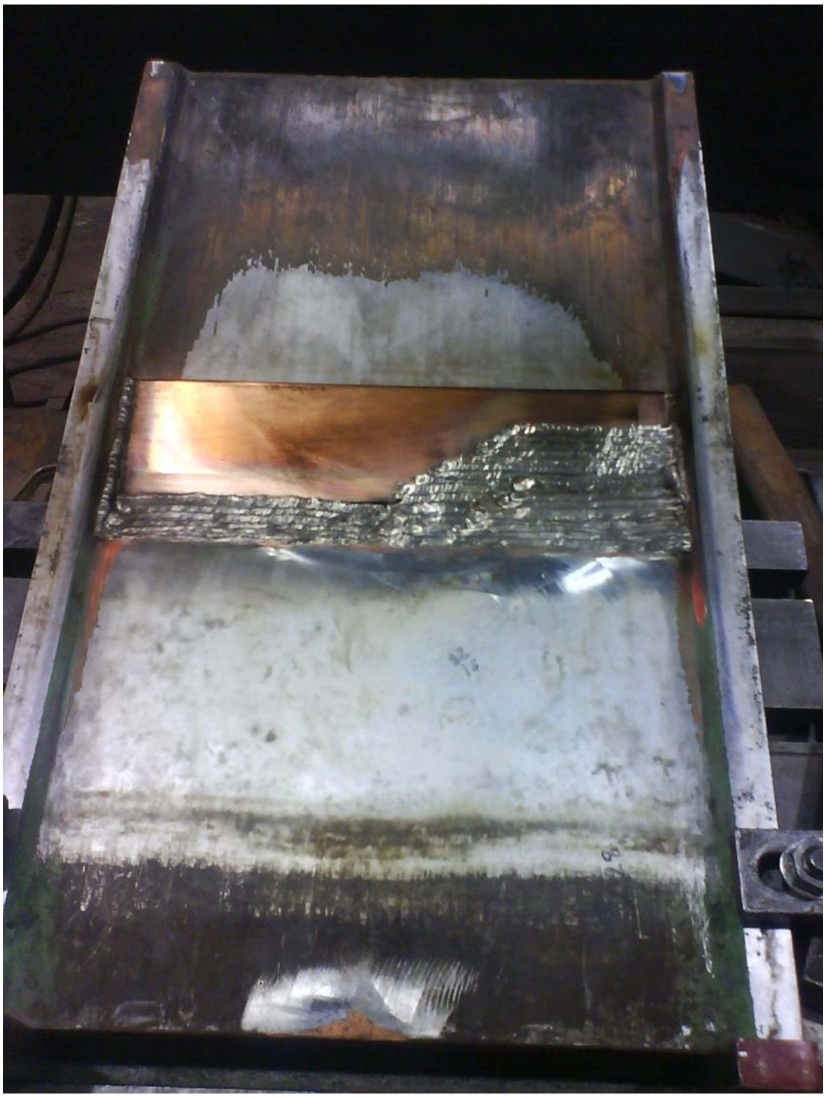

Figure 27. Wide face mould during welding operation.

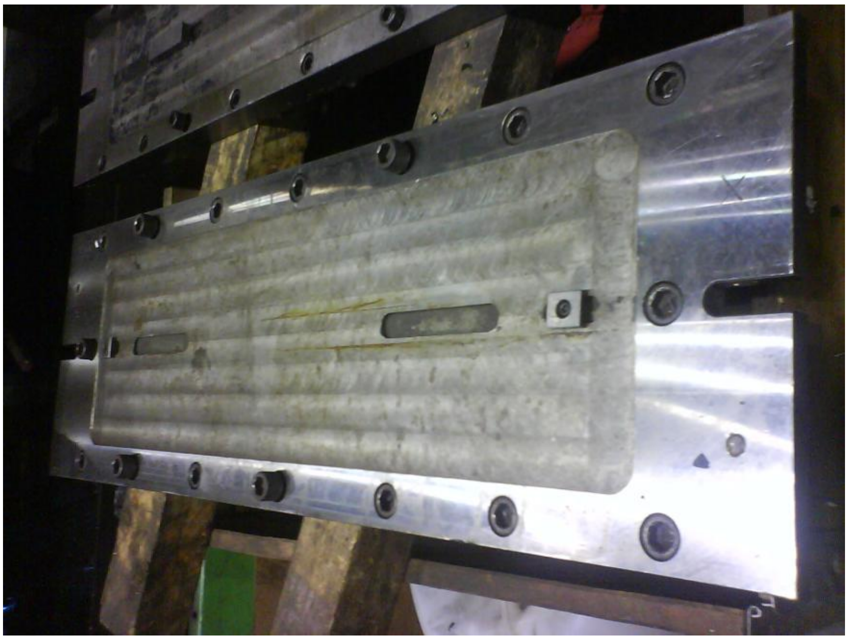

Figure 28. Bottom steel plate needed to avoid deformation of the copper mould during welding.

Figure 29. Mould after welding supervised by Leif Eklund from the maintenance department at SSAB EMEA in Oxelösund.

The trials were also in this case made at two occasions:

- The trials of the carbon steel were made 10-11th of April 2010 on three single heats, 525146, 525147 and 525148.
- The trials of the stainless steel were made the 28th of April 2010 on three single heats, 525285, 525286 and 525287.

The CC-machine at SMT is a three strand bloom machine where the soft cooled mould in all trials was situated on the loose side in strand no. 3.

All heats were made without complications and the data logging worked perfectly with access to all T.C's.

The following variables were followed up from the experiments:

<u>From the CC-process logging system:</u>

- Tundish temperature
- Casting speed
- Cooling effect in the mould
- Steel level

<u>From Swerea KIMAB's data logging</u>

18 temperatures from each broad side mould.

<u>From manual sampling</u>

- Mould powder- and slag depth.
- Slag sampling from the mould.

<u>From the slabs</u>

From each heat one slab was put aside for later measurement of the surface topography regarding oscillation mark depth with the aid of Swerea KIMAB's laser equipment.

From heat 525146 (carbon steel) and heat 525286 (stainless steel) a slice was taken out for metallographic examination.

4.3.2 Process data

The average tundish temperatures and casting speeds are shown in Table 14.

Table 14. Average tundish temperatures.

Heat no.	Steel grade	Casting speed, m/min	Temperature, °C
525146	Carbon steel	0.76	1533
525147	"	0.78	1537
525148	"	0.74	1540
525285	Stainless steel	0.78	1475
525286	"	0.78	1472
525287	"	0.83	1473

The casting speed could however show some variations which is exemplified in Figure 30. The steel level is also deliberately varied to spread the chemical attack on the sub emerged nozzle (SEN) which is exemplified in Figure 31. For a correct modelling it was therefore very important to select stable periods both in regards of casting speed and steel level.

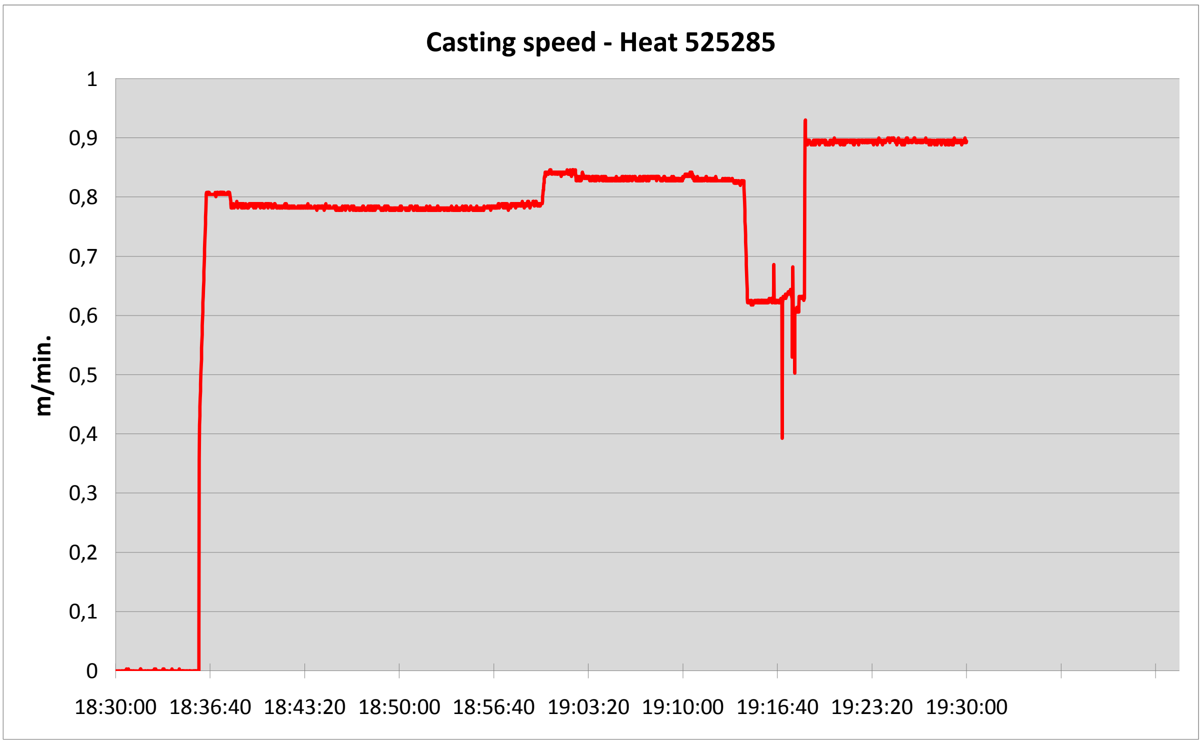

Figure 30. Casting speed for heat no. 525285.

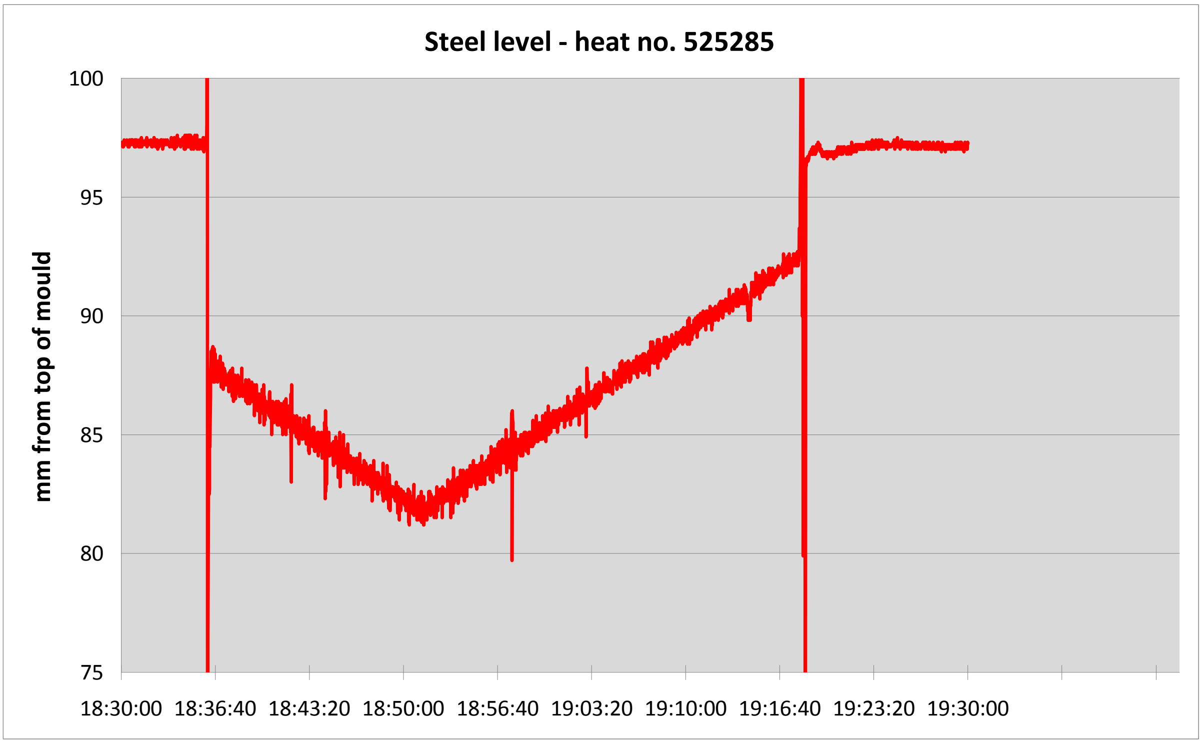

Figure 31. Steel level for heat no. 525285

The heat flux from the mould is calculated with data as: Temperature difference between incoming and outgoing water, water flow and mould area that is in contact with the steel based on information shown in Figure 31. The heat flux differs a lot for the stainless steel and the carbon steel which previously have been shown for the reference trials. In Figure 32 heat no. 5252145 from the carbon steel is shown.

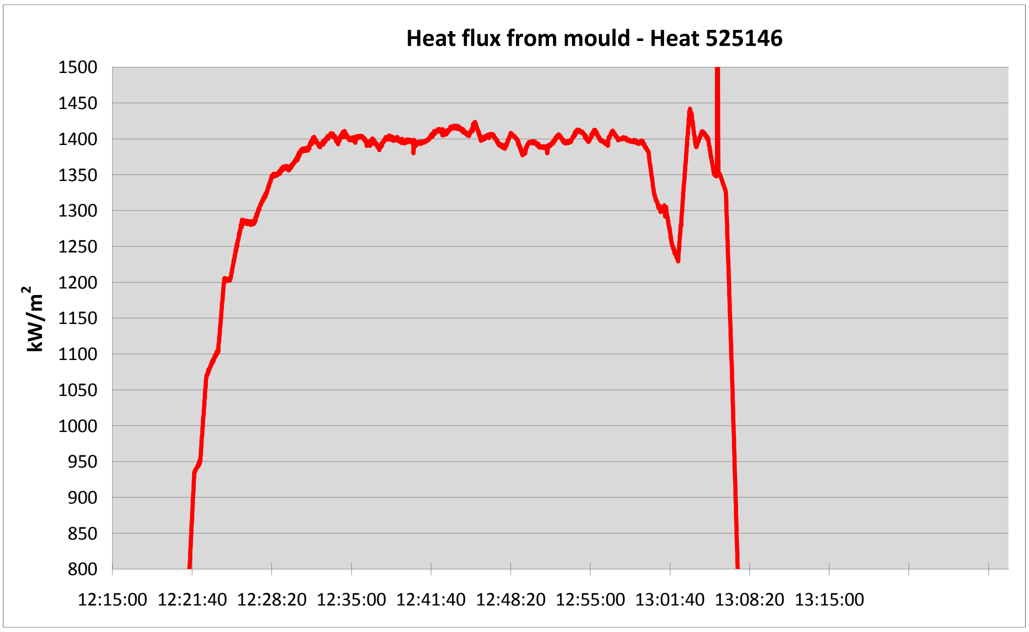

Figure 32. Heat flux from mould in heat no. 525146.

At start the mould is cool so it takes about 10 minutes until the heat flux show correct values. During the period with constant casting speed the heat flux is rather stable at a high level.

In Figure 33 the heat flux from the stainless steel heat 525287 is shown.

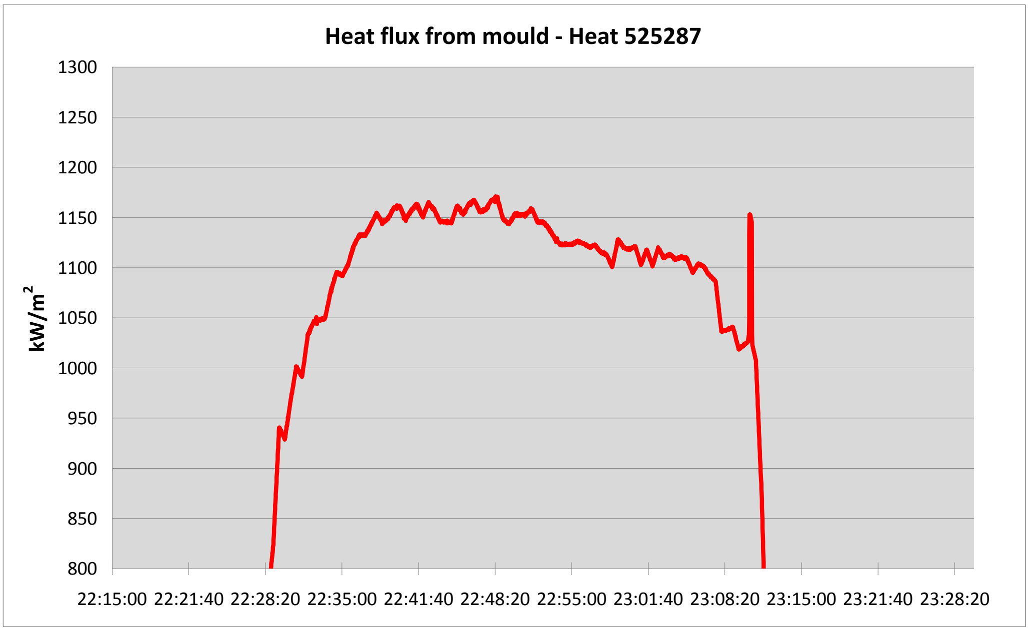

Figure 33. Heat flux from mould in heat no. 52587.

The curve is typical for a casting with a mould flux with high crystallisation rate. The casting is started with a starting powder with a low basicity which results in a relative high heat flux. When the standard powder comes into operation it gradually develops a thicker, more insulating layer of mould slag between mould and strand. This layer will also more effectively absorb the irradiative heat flux in the upper part of the mould. The large difference in heat flux between the carbon and stainless steel is partly dependent upon the difference in crystallisation rate of the mould slag but other variables are difference in steel temperature of about 60 degrees and the lower conductivity of the stainless steel.

4.3.3 Slag composition and slag rim

During the experimental castings slag samples were taken out from the mould which were analysed at the laboratory in Sandviken. From the composition theoretical calculations have been made to achieve information regarding the properties of the mould slags which is shown in Table 15. The viscosity is calculated with the Ribaud formula [ref. 12] and the NBO/T (Non Bridging Oxygen/Tetraeder) from Ken Mills [ref. 9]. Cuspidine is the most common crystal type for these slag systems and the theoretical calculation is a pure stoichiometric calculation for the bonding of cuspidine with the formula $3CaO{\cdot}2SiO_2{\cdot}CaF_2$.

Table 15. Important physical data for mould slag collected from the mould.

Mould powder	**For carbon steel**	**For stainless steel**
Basicity (Cao/SiO_2)	0.97	1.29
Basicity((CaO+MgO/SiO_2+Al_2O_3)	0.69	1.00
NBO/T	1.19	2.22
Theoretical cuspidine content, %	29	47
Viscosity η_{1300}, Poise	17.5	1.7

Conclusions:

- The mould slag from casting of the carbon steel has a high viscosity and low tendency for crystallisation which can be seen both from the low NBO/T number and theoretical cuspidine content. A fully amorphous mould slag film between mould and steel shell is to be expected.
- The mould slag from the casting of the stainless steel has a low viscosity and a high tendency for crystallisation which is seen from the high NBO/T and also theoretical cuspidine content which however is limited by a rather low level of fluorine. A fully or partly crystalline mould slag film is to be expected.

At the end of casting, when the strand was going out of the mould, it was possible to get samples from the slag rim and some slag layer beneath the rim. Normally this is impossible for the mould slag for the carbon steel because it has a very thin slag rim and amorphous slag film. Thanks to a rough surface of the soft cooled mould it was stuck to the surface making this unique sampling possible.

Some pictures from slag rim and slag films from the soft cooled side are shown in Figures 34-43.

<u>Stainless steel, heat no. 525287</u>

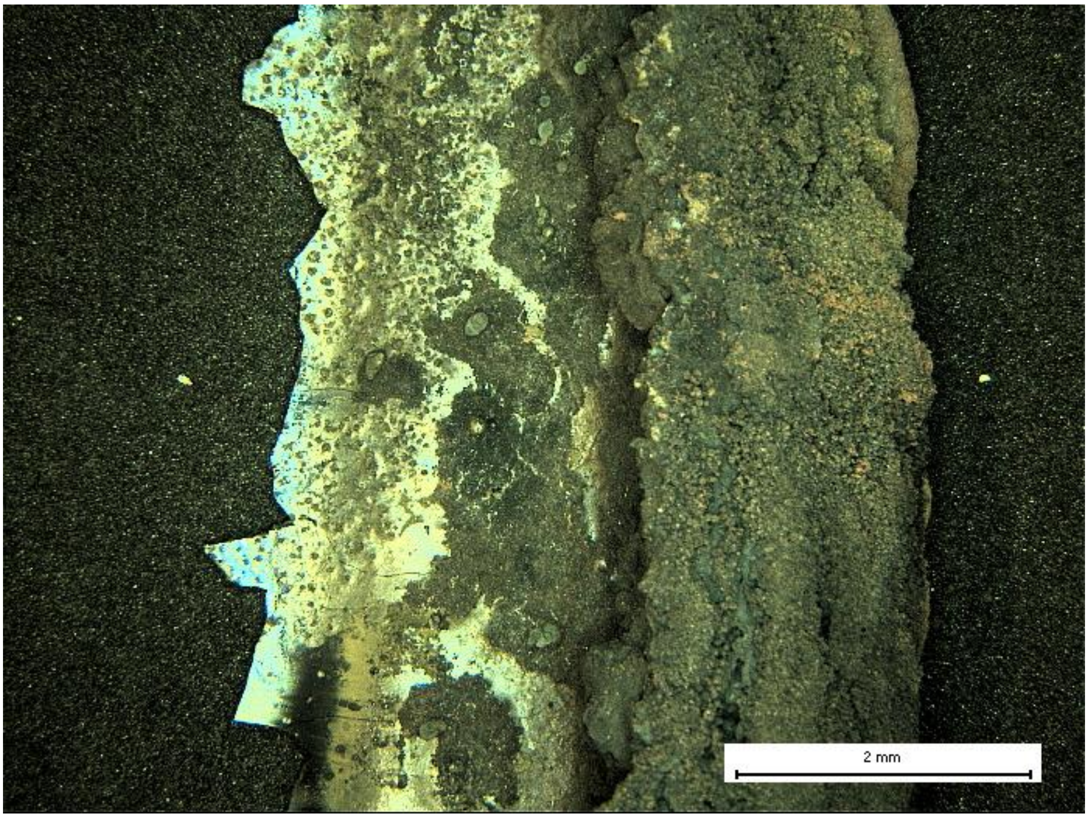

Figure 34. Slag rim.

Figure 35. Cross section from lower part of the slag rim, partly crystallised from mould surface.

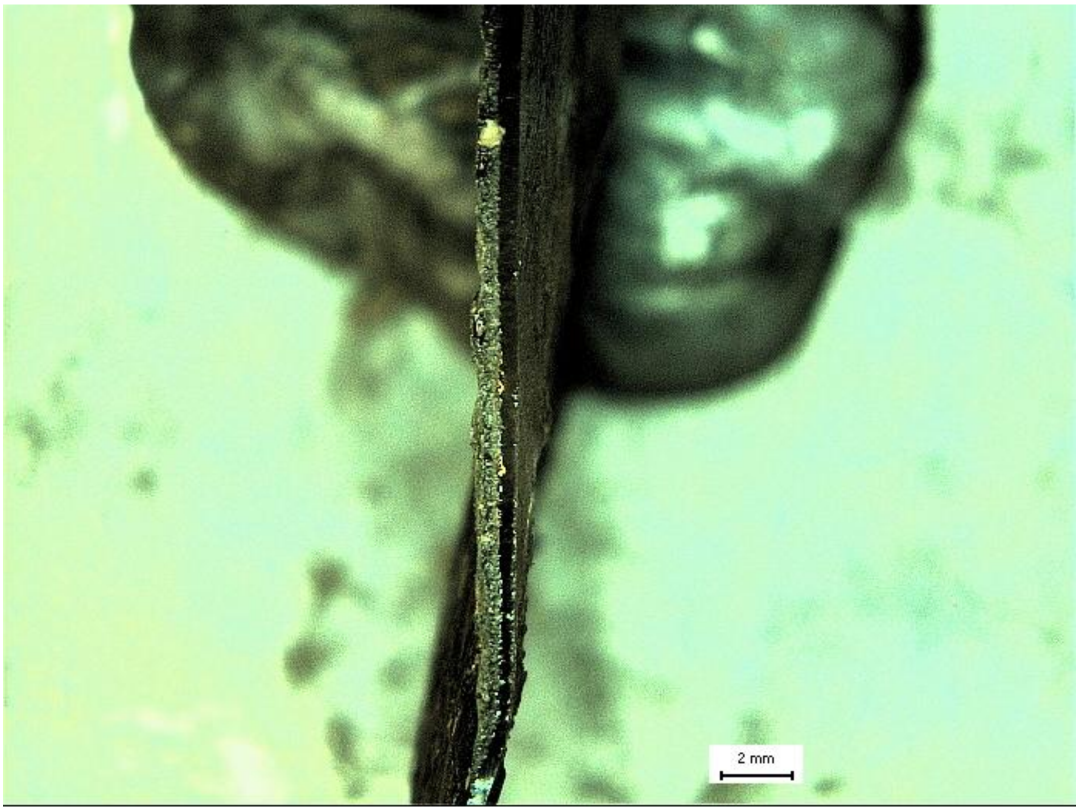

Figure 36. Cross section from a slag film just below the slag rim.

Figure 37. Cross section from slag film lower down the mould.

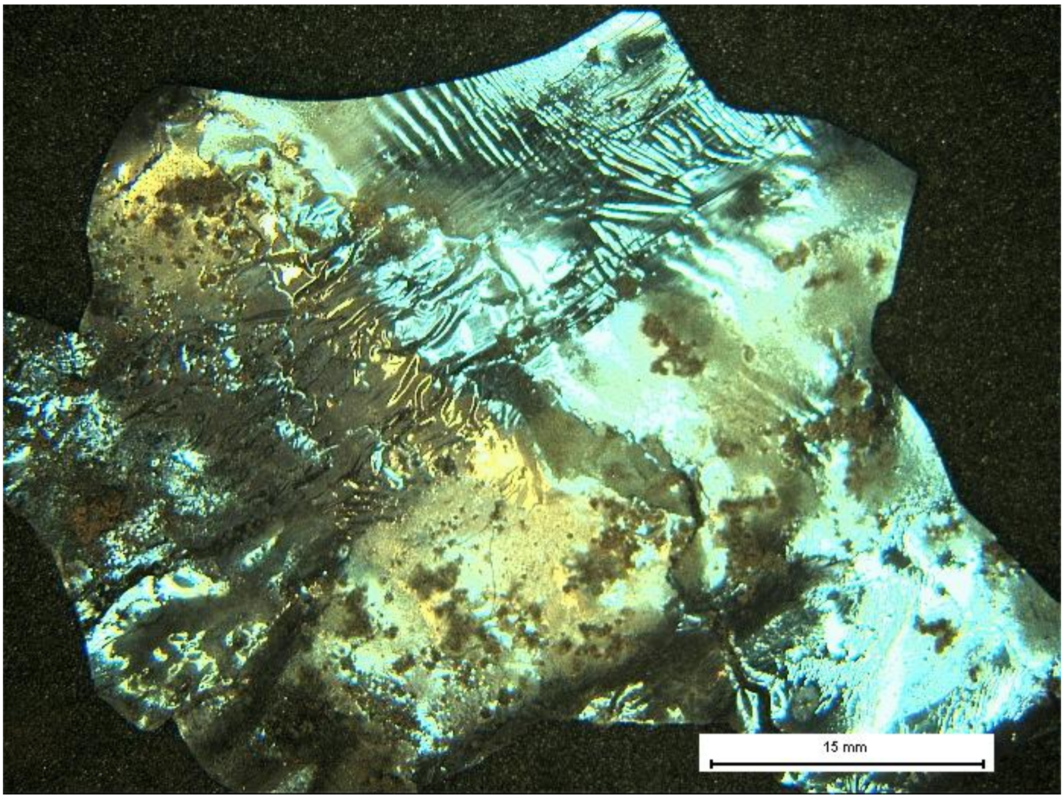

Figure 38. Surface against steel shell for slag film in Figure 36.

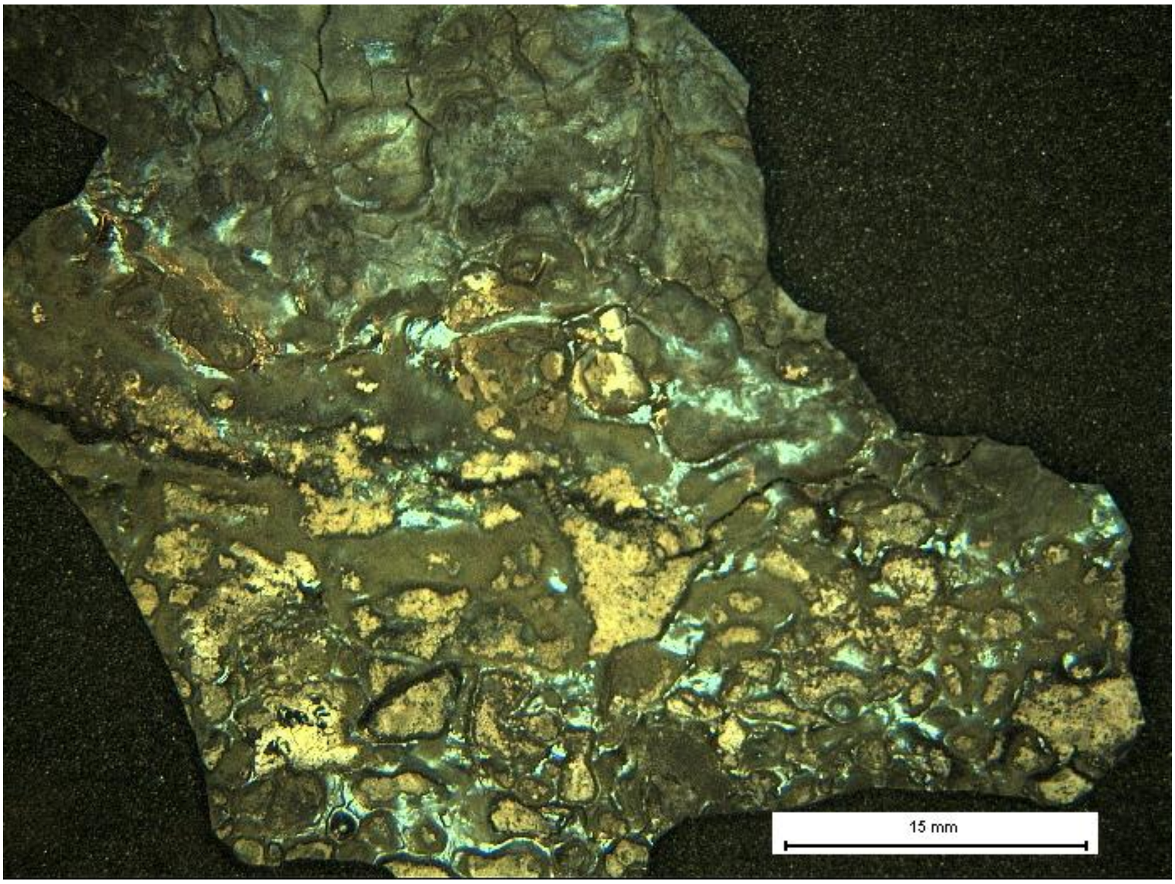

Figure 39. Surface against mould for slag film in Figure 36.

Conclusions:

- Thick fully crystallised slag rim in the upper part
- Downwards the mould a slag film of about 0.5 mm is seen which is crystallised to about 60 % from the mould side.
- Further down the mould the slag film become thinner, about 0.4 mm and more crystallised (about 80 %).

It must be noticed that the thicknesses of the investigated slag films are thicker than in normal operation due to reduction of casting speed in connection to the finish of casting and cladding of the slag film from the top slag coming down with mould.

Carbon steel, heat no. 525146

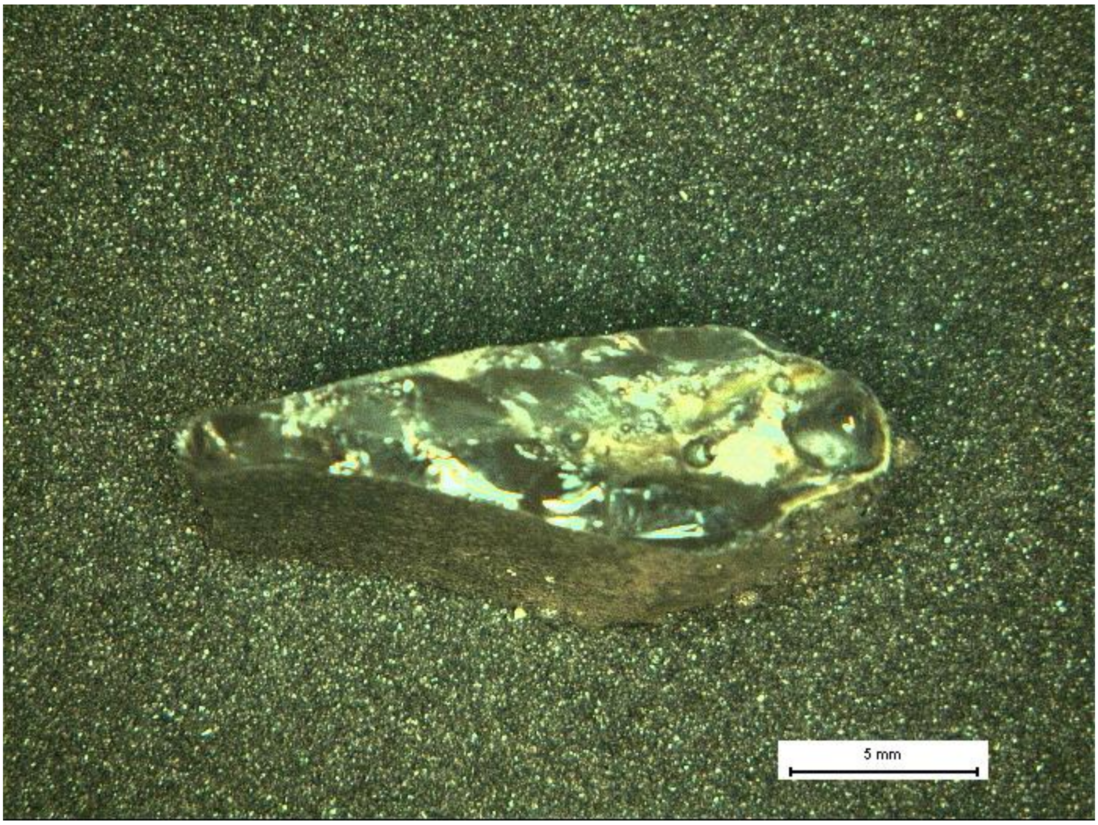

Figure 40. Slag rim partly crystallised in the upper part.

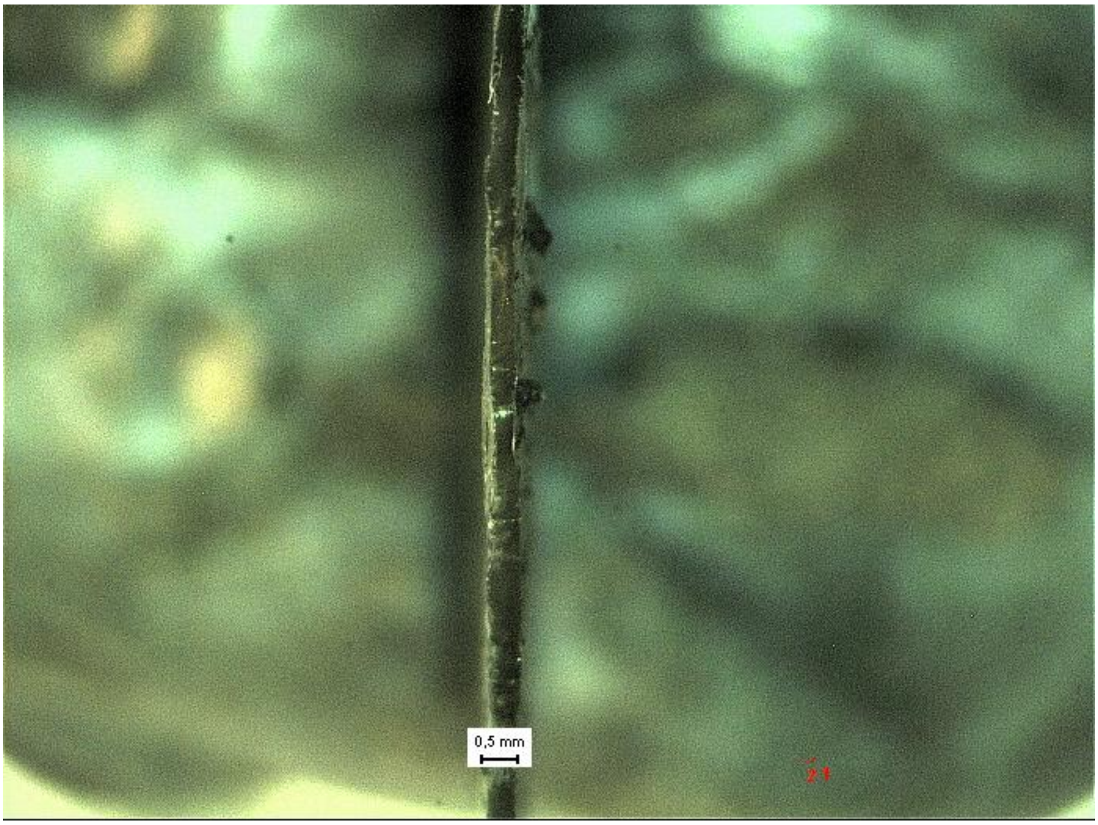

Figure 41. Cross section of slag film just below the slag rim.

Figure 42. Surface against mould for slag film in Figure 41.

Figure 43. Cross section of slag film further down the mould.

Conclusions:

- A small slag rim is formed which is partly crystallised in the upper part.
- Downwards the mould a slag film of about 0.3 mm is seen which is fully glassy (amorphous).
- Further down the mould the slag film has about the same thickness and does not crystallise.

4.3.4 Temperatures in the mould

The basic ambition when evaluating the temperature measurements from the T.C's was to give input data for the modelling work where temperature distributions and most interesting heat flux can be evaluated. In designing the experiment the depth of the soft cooling layer was decided to be 8.5 mm which would decrease the heat flux with 20 %. This has to be proved by evaluation with the shell formation model developed in the platform COMSOL Multiphysics.

For that reason the mean temperatures for a period of 6 minutes have been calculated at stable periods 15 minutes after start of casting where the steel level is highest and most stable according to Figure 31. Because changes in heat flux was obvious during the casting for the stainless steel (see Figure 33) mean values for a 6 minute period were also calculated for the also stable period 30 minutes after start of casting.

In addition to the mean values there is a lot of information that could be drawn from the temperature measurements where it must be emphasised that the installation of thermocouples and data acquisition were perfect thanks to an excellent work done by Christer Eggertsson from Swerea KIMAB and Kurt Svahn from Sandvik Materials Technology. In Figure 44 the temperatures from the highest situated T.C's are shown for the carbon steel heat no. 525146.

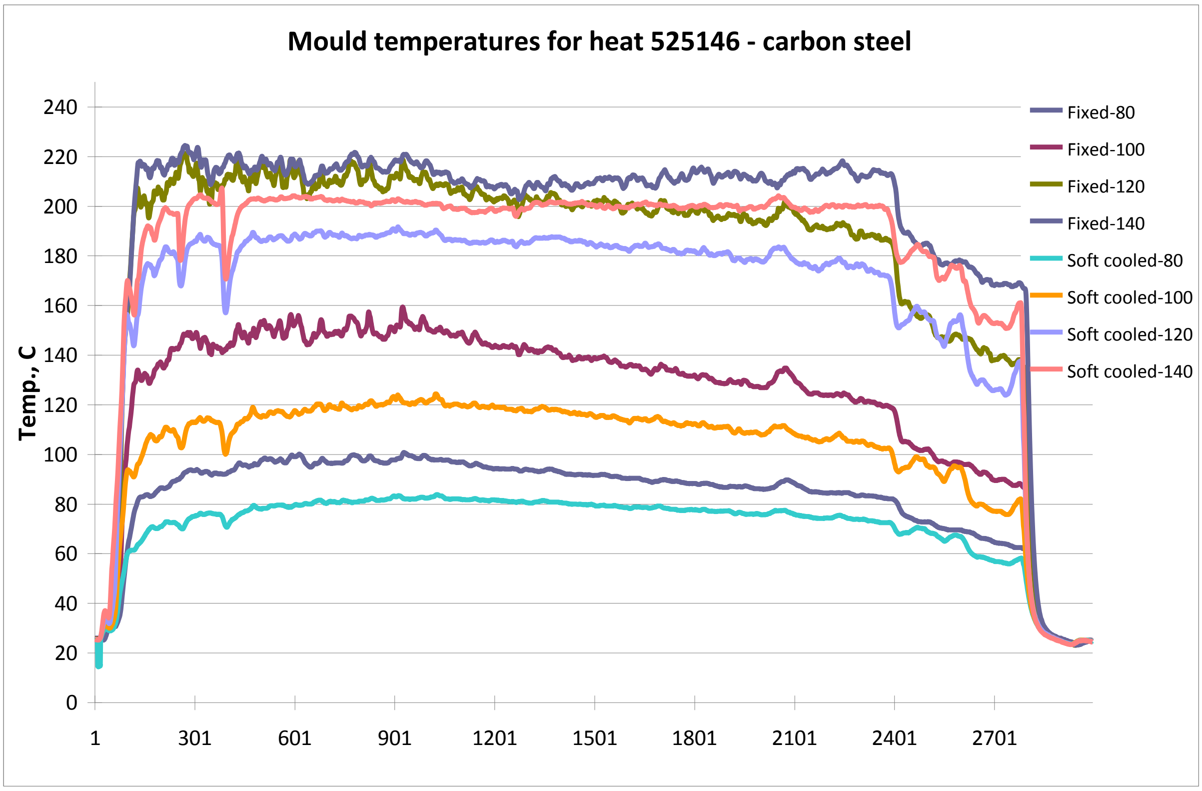

Figure 44. Mould temperatures in the upper part of the mould for carbon steel heat 525146.

Conclusions:

- The steel level varies from 90 to 82 mm from the upper surface. These variations are clearly seen in T.C. 80 (placed above the steel surface) and T.C. 100.
- At lower positions, T.C. 120 and 140 the mould temperatures are no longer influenced by the steel level. The temperature level is very stable until changes emerge in casting speed.
- There is an obvious difference in mould temperatures between the fixed- and soft cooled mould but it must be noticed that the T.C:s in the soft cooled mould are situated 5 mm deeper from the surface compared to the fixed mould.

In Figure 45 the corresponding graph is shown from the stainless steel heat no 525287.

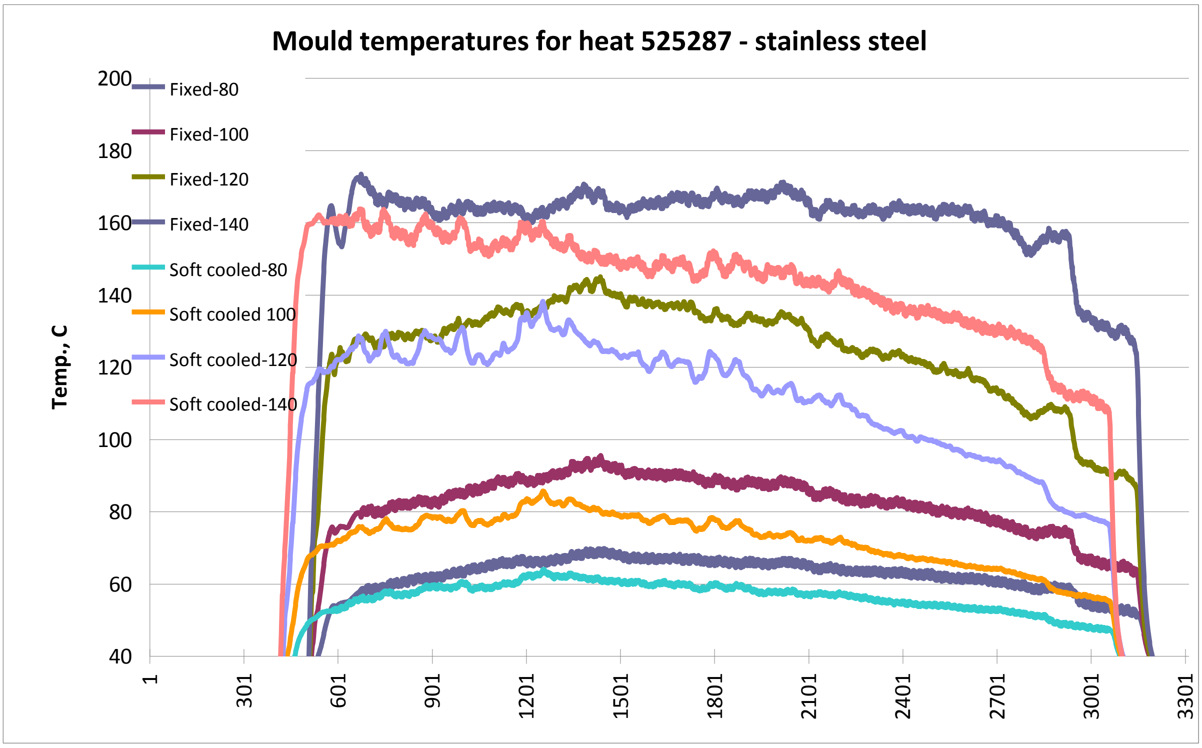

Figure 45. Mould temperatures in the upper part for stainless steel heat 525287.

Comments:

- About the same pattern as for the carbon steel but at much lower temperatures.
- A large difference is that the soft cooled mould in the 140 mm position show decreasing temperatures all through the casting which is not the case for the fixed mould. This could be a consequence of the continuous development of a thick layer of mould slag on the soft cooled mould.
- The appearance of temperature at the 140 mm level for the soft cooled mould could also be found on heat no. 525286 but not on heat no. 525285.

The temperatures at the lower part of the mould for the carbon steel, heat 525146 are shown in Figure 46.

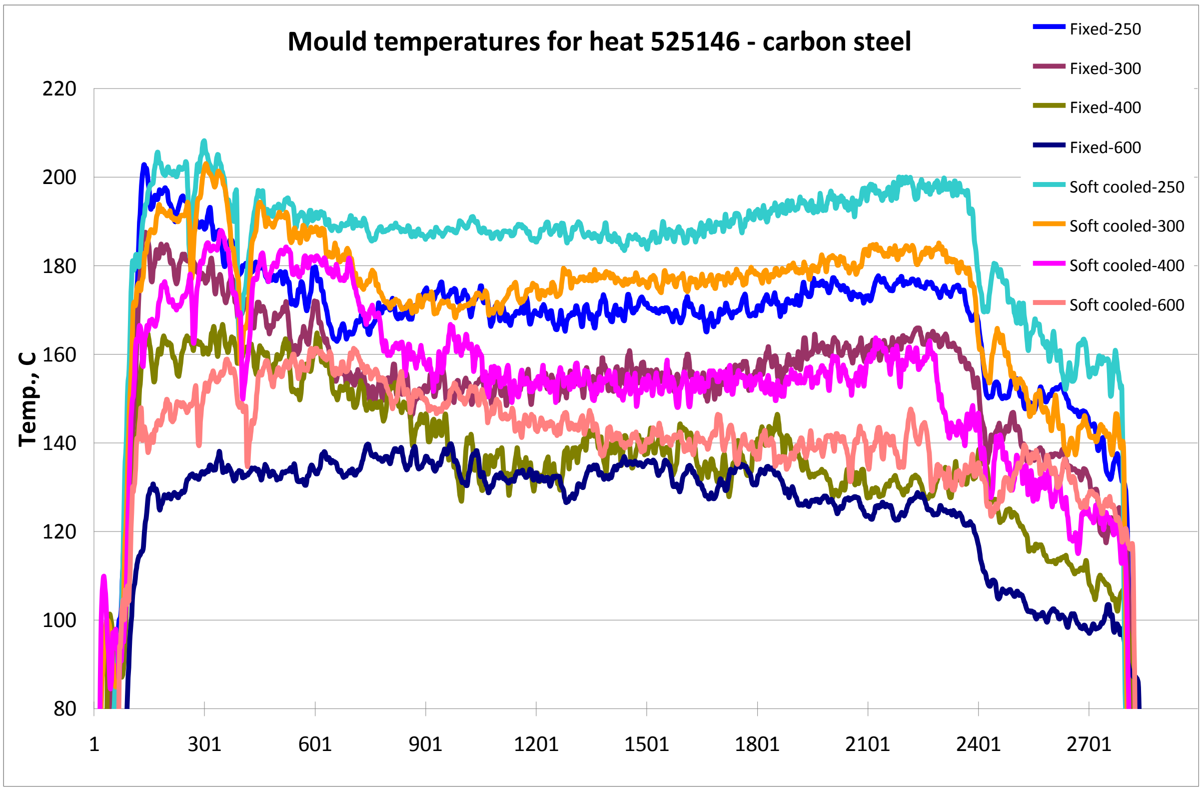

Figure 46. Mould temperatures in the middle and lower part of the mould for carbon steel 525146.

Conclusions:

- The nickel wedge goes from 80 mm down to 200 mm in the mould and from position 250 mm the T.C's are placed on the same distance from the surface (10 mm) for both mould which make them comparable.
- It is obvious that the steel surface comes down from the wedge position hotter than in the fixed mould. There is a temperature difference of about 20 °C. Part of this can be attributed to the normal difference between loose and fixed side according to the measurements from the reference trial but about 10 °C is because of the soft cooling.
- Down to 400 mm the temperature curves have the same pattern but at gradually lower temperatures. This means that the steel shell is formed with good mould contact.
- The temperature at 600 mm has a different appearance as a consequence of less contact with the mould.

The corresponding figure for the stainless steel 525287 is shown in Figure 47.

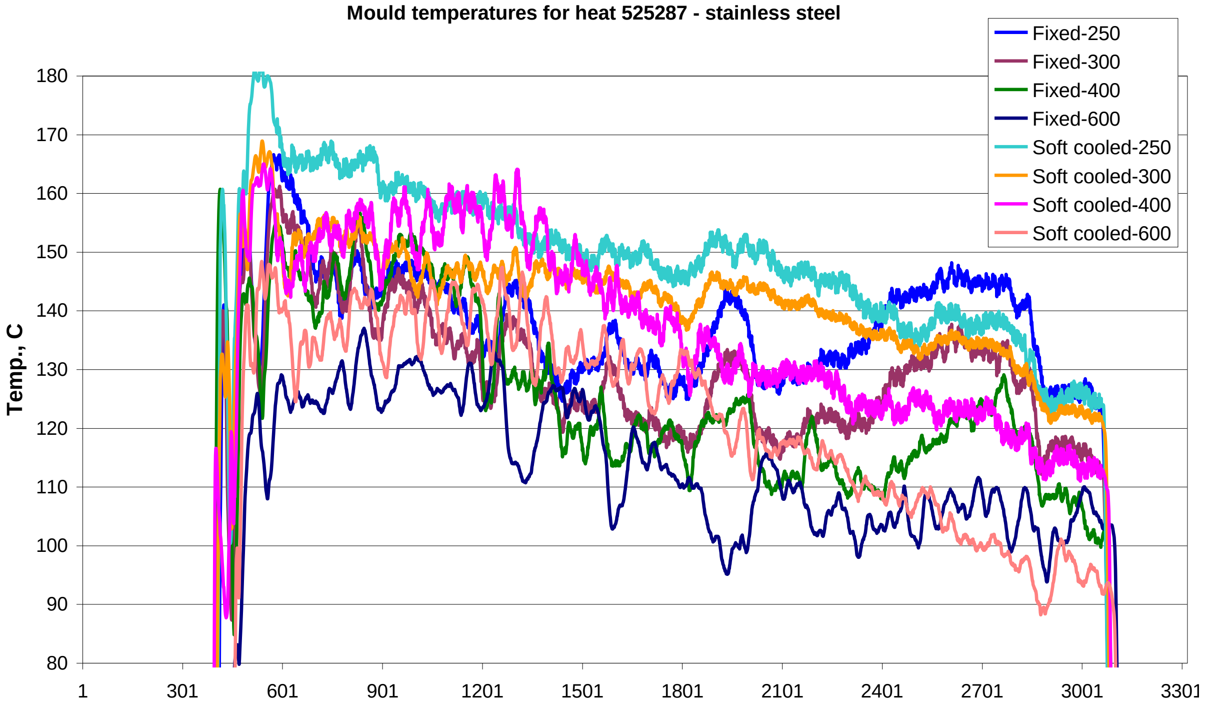

Figure 47. Mould temperatures in middle and lower part of the mould for stainless steel 525287.

Conclusions:

- Much lower temperatures and variations compared to the carbon steel.
- Strongly falling temperatures with time as a consequence of gradually growing mould slag film.
- The same temperature profile down to 300 mm. From 400 mm it seems that the steel shell has lost contact and shows strong variations (rebound effect).

In the 600 mm position two thermo couples were mounted, one 10 mm from the surface and the other 20 mm. From the modelling work it has been found that the isotherms at this position are perfectly parallel which makes it possible to calculate the heat fluxes at this position, which are shown for all experimental heats in Figures 48-53.

Conclusions for the carbon steel:

- At the start of the casting there is an obvious much higher heat flux in the soft cooled side which changes with the casting time and become more equalized.
- At the end of casting the heat flux could be higher for the fixed side.

Conclusions for the stainless steel:

- Same tendencies as for the carbon steel but much lower level of heat flux.
- As a consequence of a softer shell much larger variations in the heat flux could be found especially for the soft cold mould.

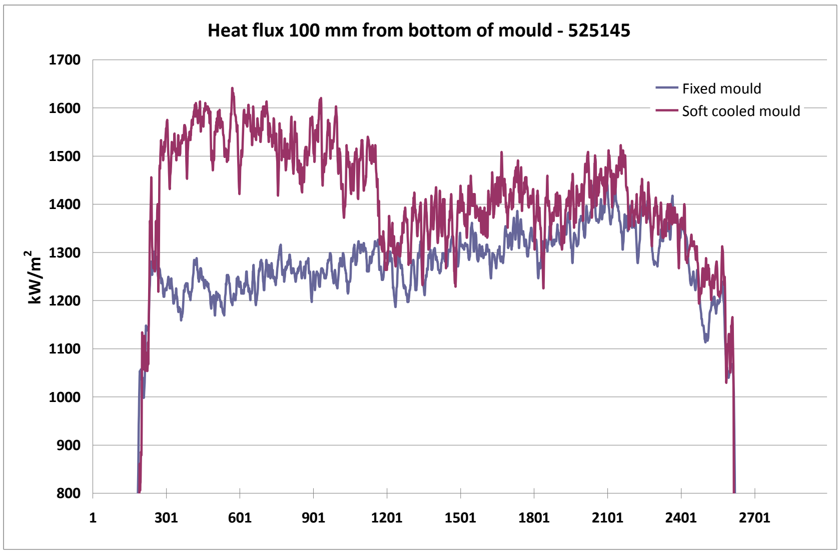

Figure 48. Heat flux at bottom of mould for carbon steel – 525145.

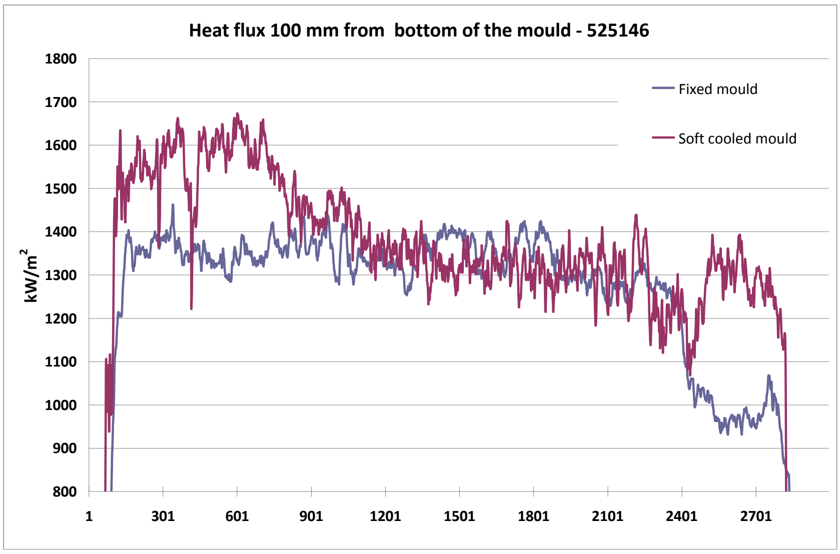

Figure 49. Heat flux at bottom of mould for carbon steel – 525146.

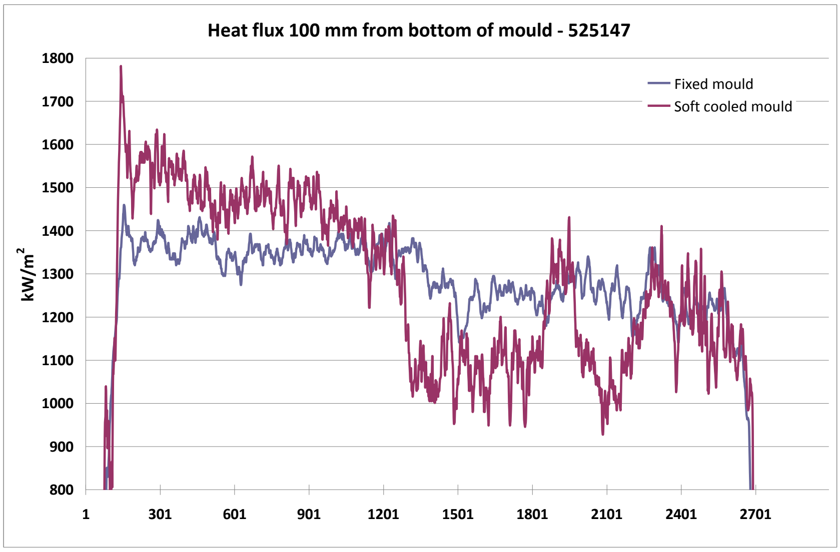

Figure 50. Heat flux at bottom of mould for carbon steel – 525147.

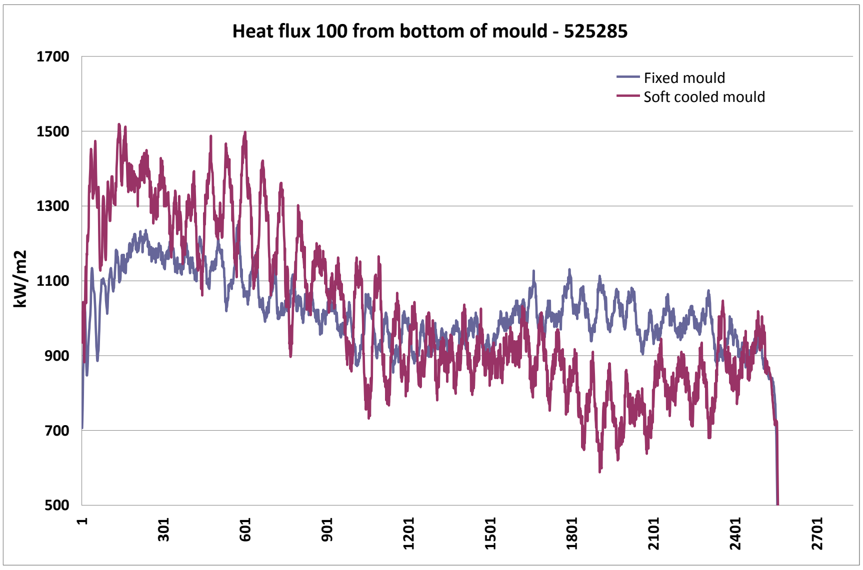

Figure 51. Heat flux at bottom of mould for stainless steel – 525285.

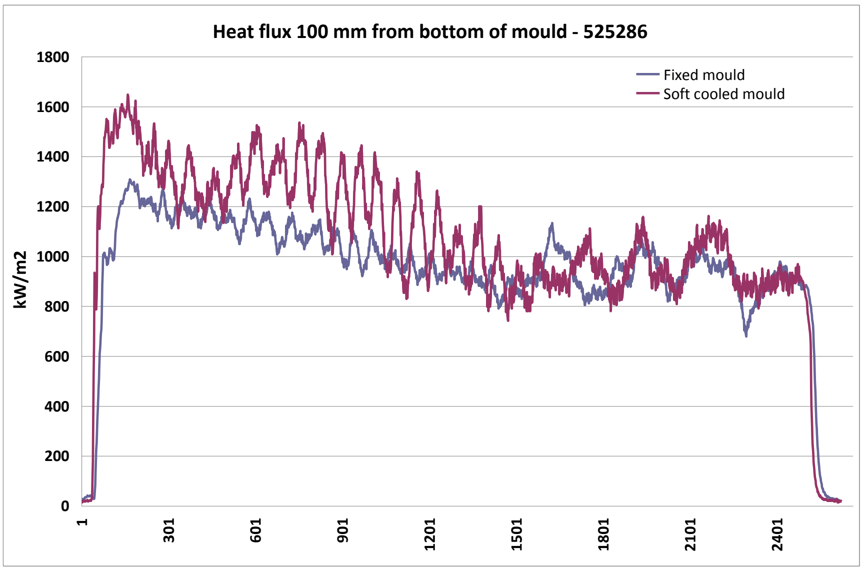

Figure 52. Heat flux at bottom of mould for stainless steel – 525286.

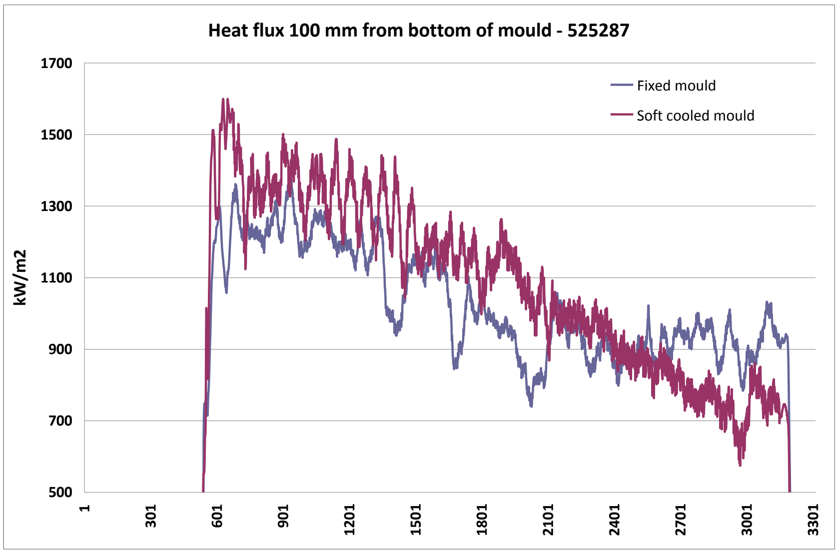

Figure 53. Heat flux at bottom of mould for stainless steel – 525287.

The mean values of the temperatures from the carbon steel are rather equal for all heats and also at different times of the casting which are exemplified in Figures 54 and 55 from heat 525146.

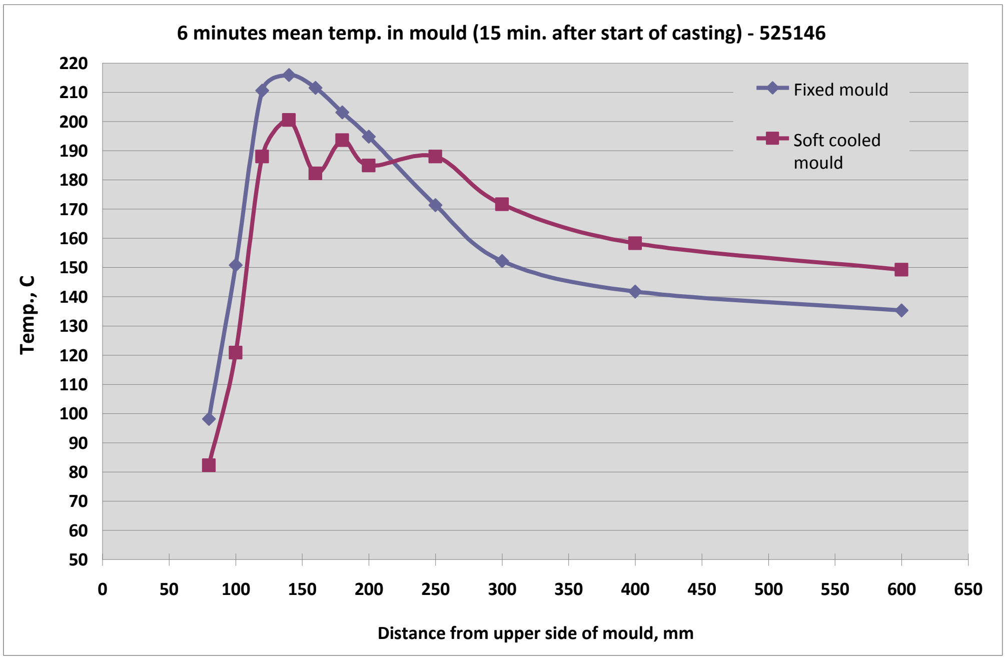

Figure 54. Mean temperatures 15 minutes from start of casting for carbon steel – 525146.

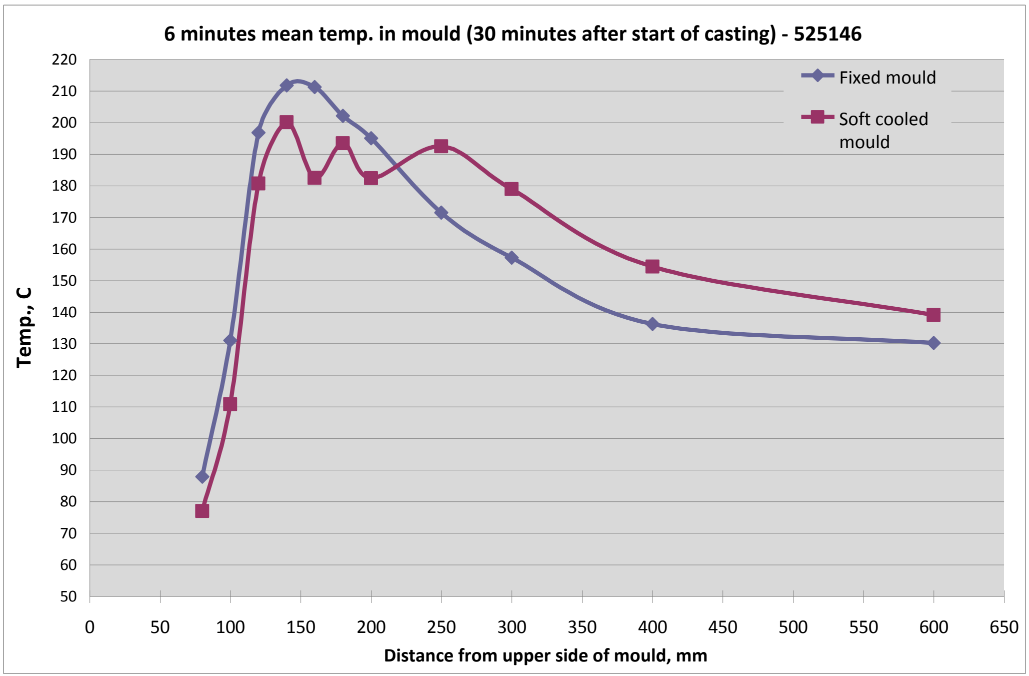

Figure 55. Mean temperatures 30 minutes from start of casting for carbon steel – 525146.

Conclusions:

- When the T.C's are comparable (same distance from surface) 250 mm from the upper side the soft cooled side is warmer than the fixed side and this is the case all down the mould.
- From the reference trials (Figure 24) the same pattern can be seen but with a smaller temperature difference.

For the stainless steel the same tendencies can be noticed but there is a great difference between 15 minutes and 30 minutes after casting which is exemplified in Figures 56 -57.

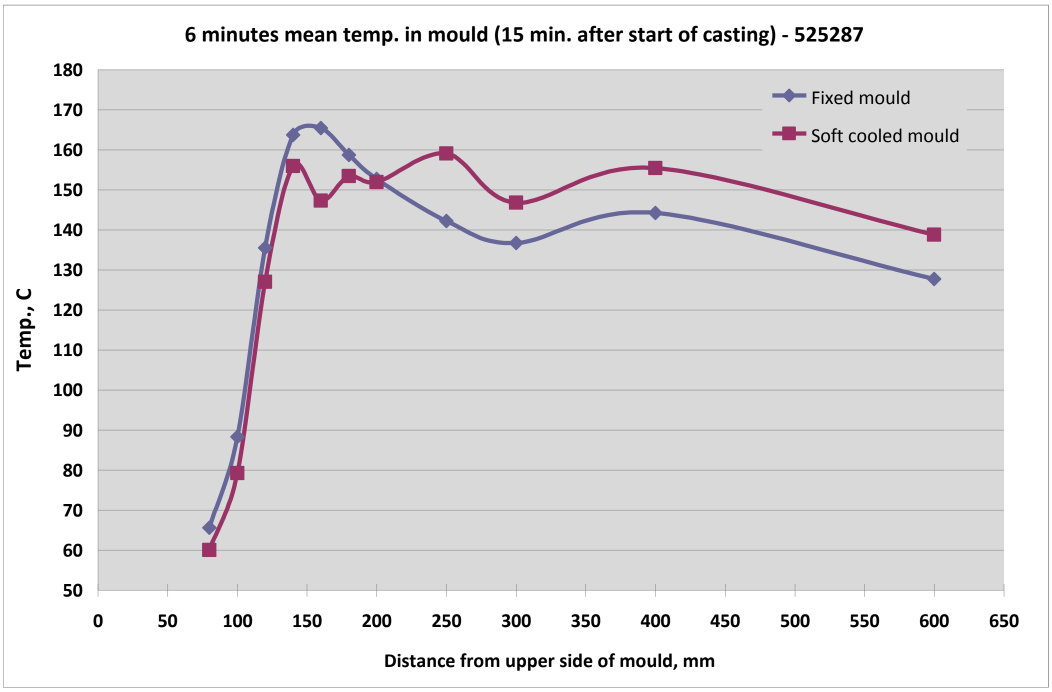

Figure 56. Mean temperatures 15 minutes from start of casting for stainless steel 525287.

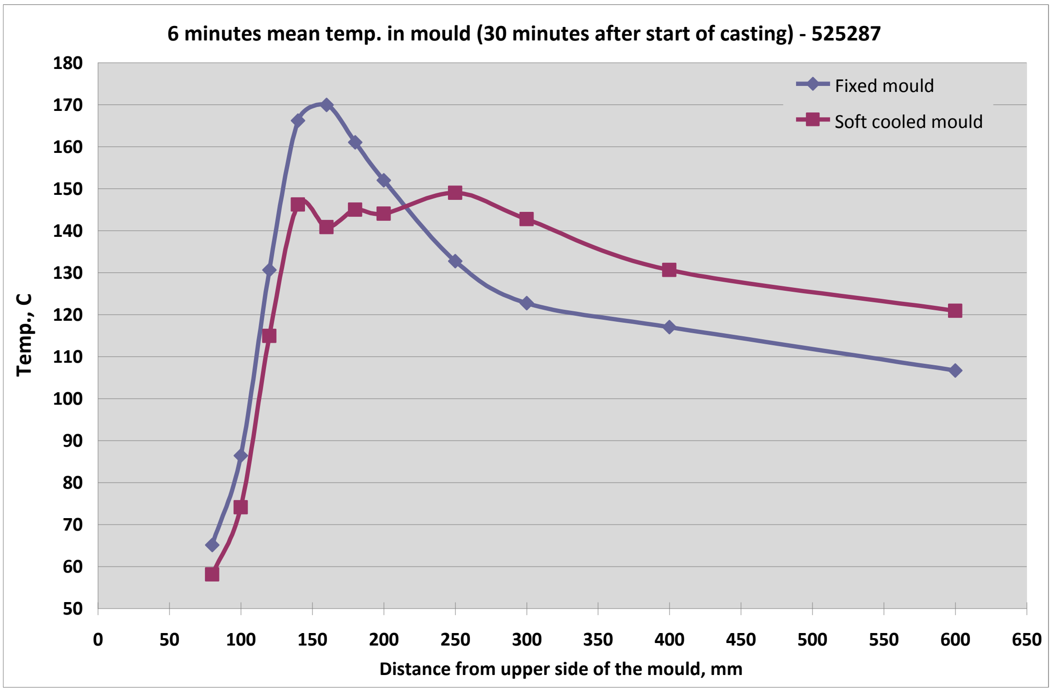

Figure 57. Mean temperatures 30 minutes from start of casting for stainless steel 525287.

4.3.5 Result from modelling with COMSOL Multiphysics

The results from the modelling activity are published in a separate report [19].

4.3.6 Results from measurements of oscillation mark depth

From all heats one bloom was saved for measurement of oscillation mark depth. As reference a bloom was taken additionally from another strand. The equipment used for the measurement has been developed by Swerea KIMAB and consist of an aluminium frame on which a laser head is installed which is moved by an electrical motor in a distance of 1800 mm. The data from the measurements are saved on a computer from where the evaluations can be made with the aid of a special program where the relative oscillation mark depth (difference between max. and min. depth) can be evaluated.

In Figures 58 and 59 pictures from the measurement and equipment are shown.

Figure 58. Johan Lönnqvist from Swerea KIMAB with the profile measurement device.

Figure 59. Data logging of surface profile from a bloom.

The oscillation parameters for the steel grades are given in Table 16.

Table 16. Oscillation parameters for the tested steel grades.

Parameter	Stainless steel	Carbon steel
Frequency, strokes/min.	200	176
Amplitude, mm	± 2	± 2

The data from the profile measurements were evaluated by Peter Andersson with the following results:

<u>Stainless steel</u>
The results from evaluation of the relative oscillation mark depth and standard deviation are shown in Figures 60-62. In Figure 63 the result from the measurement of the reference bloom are shown.

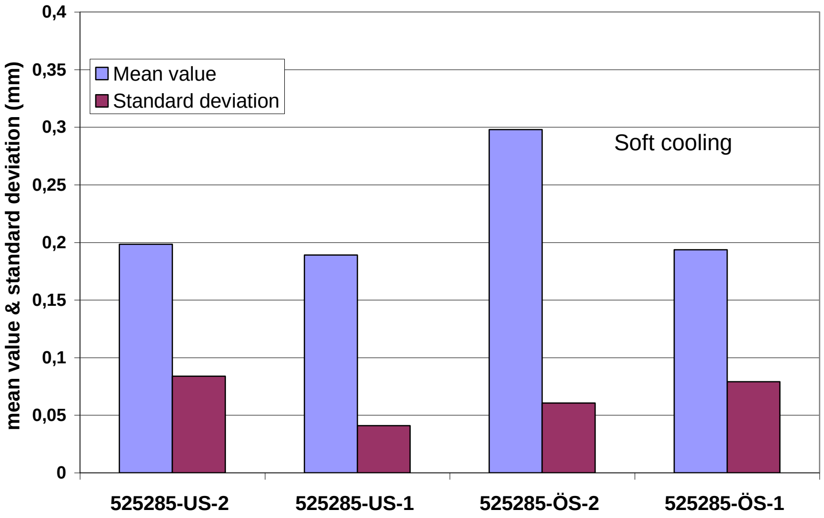

Figure 60. Relative oscillation mark depth and standard deviation for heat 525285.

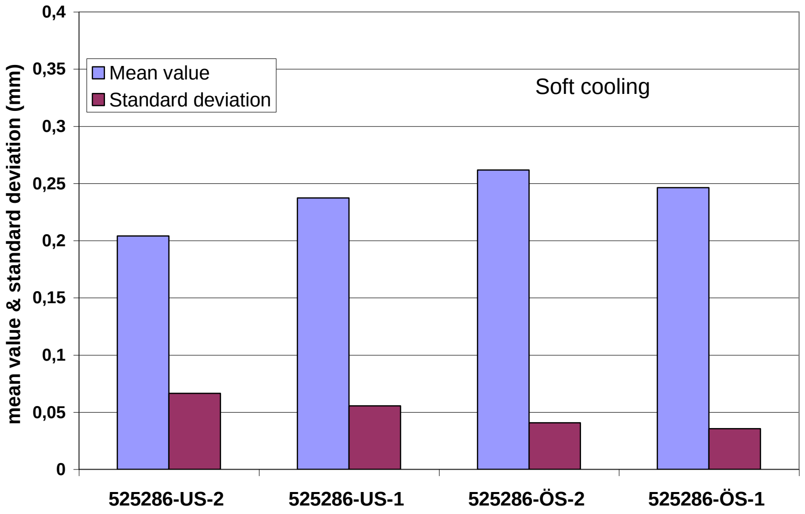

Figure 61. Relative oscillation mark depth and standard deviation for heat 525286.

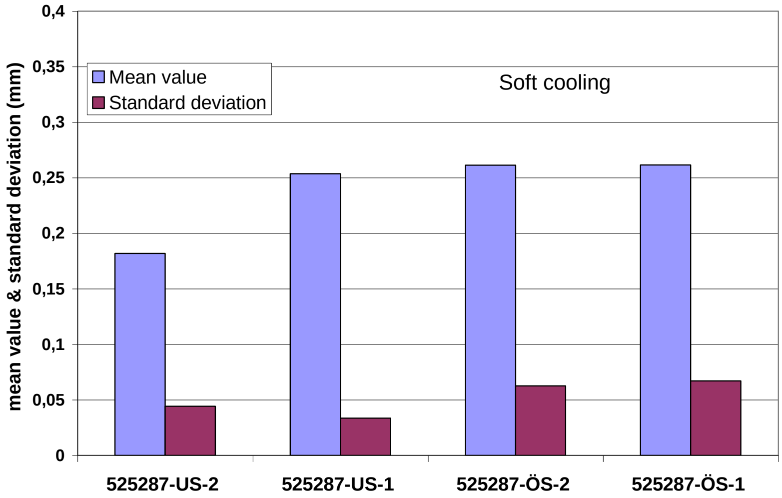

Figure 62. Relative oscillation mark depth and standard deviation for heat 525287.

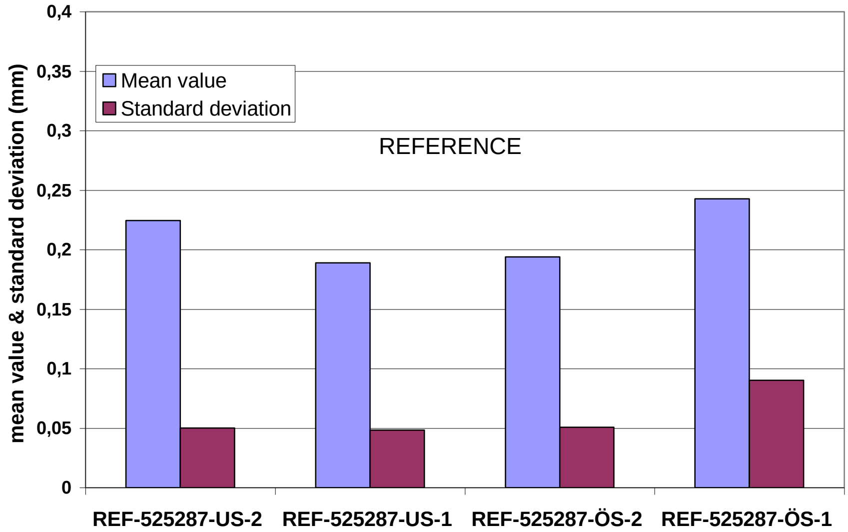

Figure 63. Relative oscillation mark depth and standard deviation for reference bloom in heat 525287.

Comments:

- Small variations between fixed and loose side on the reference bloom.
- A small but anyway obvious deeper oscillation mark depth for the soft cooled mould.
- A plausible explanation for this unexpected result could be that the soft cooled mould influences the size and appearance of the slag rim.

<u>Carbon steel</u>

The results from evaluation of the relative oscillation mark depth and standard deviation are shown in Figures 64-66. In Figure 67 the result from the measurement on the reference bloom are shown.

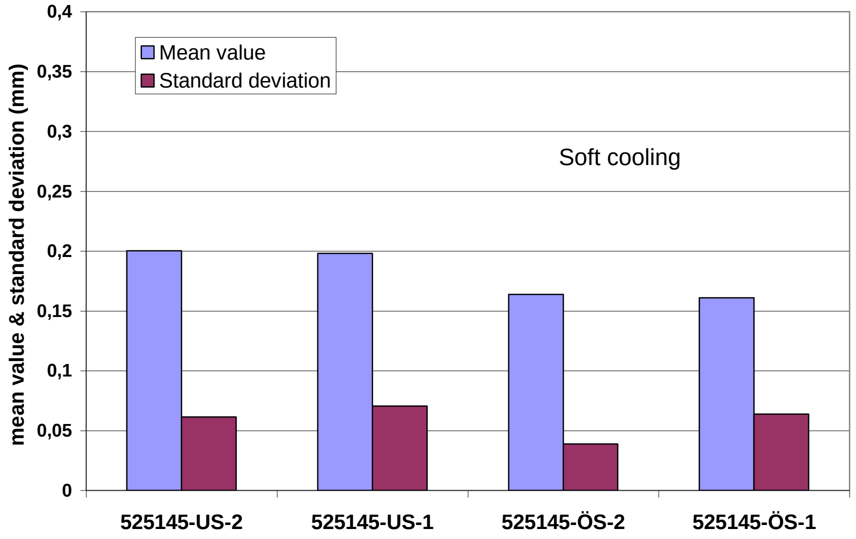

Figure 64. Relative oscillation mark depth and standard deviation for heat 525145.

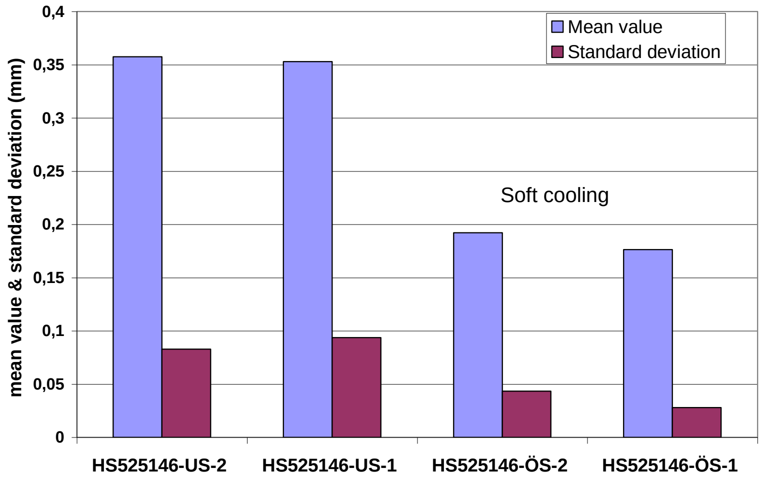

Figure 65. Relative oscillation mark depth and standard deviation for heat 525146.

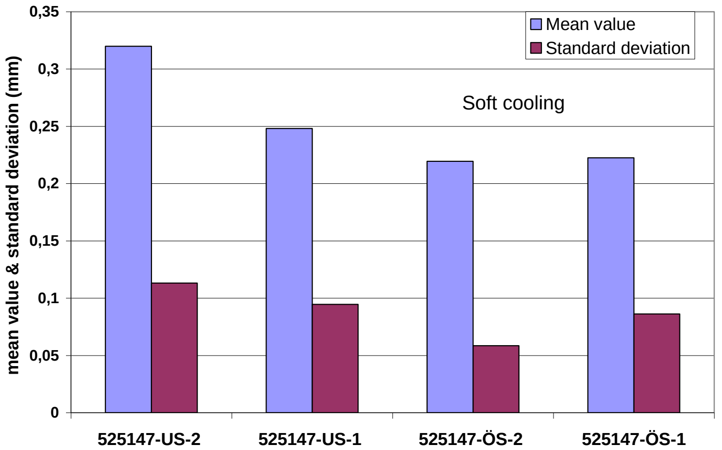

Figure 66. Relative oscillation mark depth and standard deviation for heat 525147.

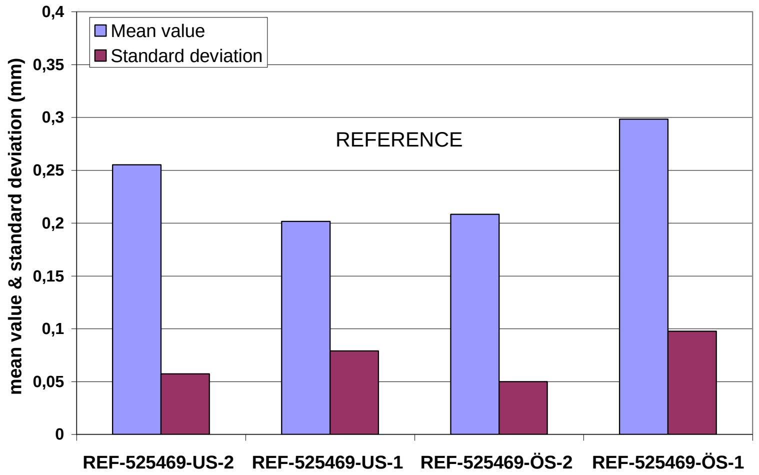

Figure 67. Relative oscillation mark depth and standard deviation for reference bloom in heat 525469.

Comments:

- Small variations between fixed and loose side on the reference bloom.
- An obvious smaller oscillation mark depth for the soft cooled mould.
- A plausible explanation for this result is that for the carbon steel with a low basicity mould powder and a very thin slag rim the soft cooled mould has a positive effect on reducing the heat flux for the initial solidification at the meniscus.

There are a large number of variables which influence the oscillation mark formation which has been extensively studied [ref. 13 and 14]. Our experience from full scale trials with slab machines is that the heat flux has a major impact on the oscillation mark depth which is illustrated in Figure 68 [ref. 15].

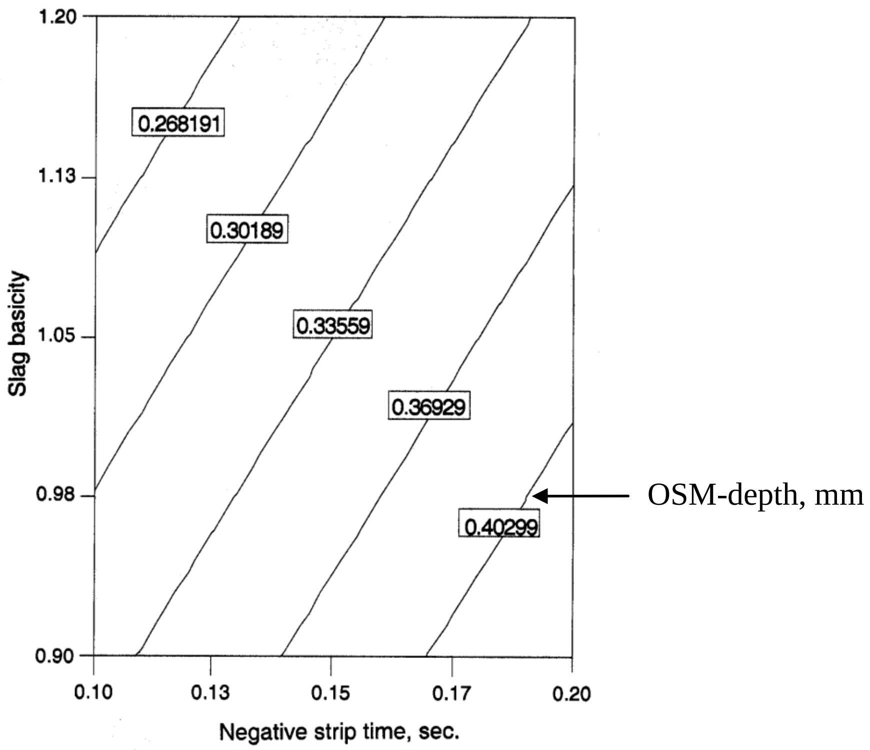

Figure 68. Oscillation mark depth as a function of slag basicity and negative strip time [reg. 15].

4.3.7 Results from the metallographic investigation.

From the stainless steel heat 525286 and the carbon steel 525146 bloom 304 and 305 slices were taken out for metallographic examination. Due to the great variations in shell formation there is a need for a much wider investigation in order to draw certain conclusions, but this small investigation can shed some light on the mystery of CC shell formation at SMT.

The preparation was made at SMT were the bloom sample were sliced in a longitudinal direction in the middle of the bloom. From the slice samples were taken out and cut in 20 mm pieces which were mounted in polyfast. The samples were sent to Swerea KIMAB where etching and metallographic examination was made.

A simple and popular way to calculate the shell thickness is the rule of thumb which states: Shell thickness (in inch) is given by the square root of casting time in minutes or shell thickness in cm is calculated as the square root of casting time in minutes multiplied with 2.5. To give an indication of the shell thickness this calculation has been made for different solidification constants in Figure 69. The nickel wedge for soft cooling covers a depth of about 110 mm from meniscus which means that the shell thickness according to Figure 69 should be about 10 mm at that position. Of that reason only the sample from the first 20 mm from the surface has been studied.

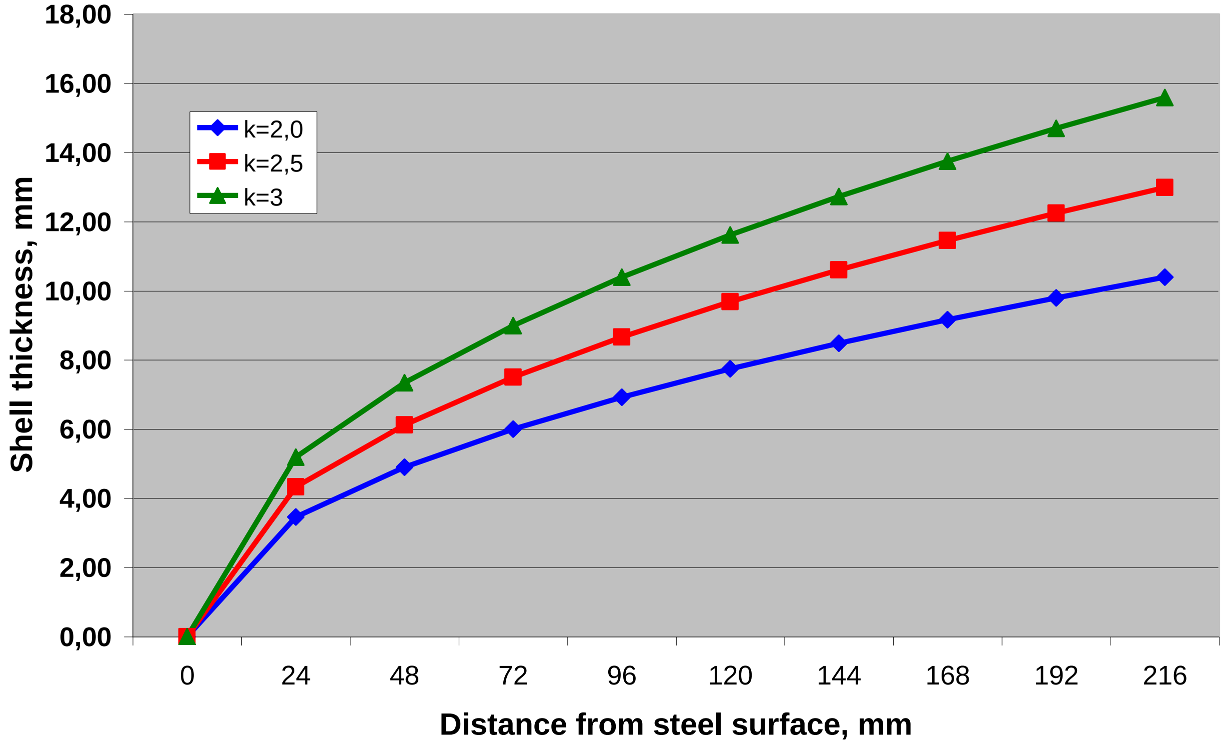

Figure 69. Calculated shell thickness according to the role of thumb for different solidification constants.

Stainless steel

The samples were etched with aqua regia. The surface was carefully studied and it was obvious that no oscillation mark “hooks” could be found neither on the soft cooled side nor on the fixed side. A typical example of the surface is shown in Figure 70 for the fixed mould.

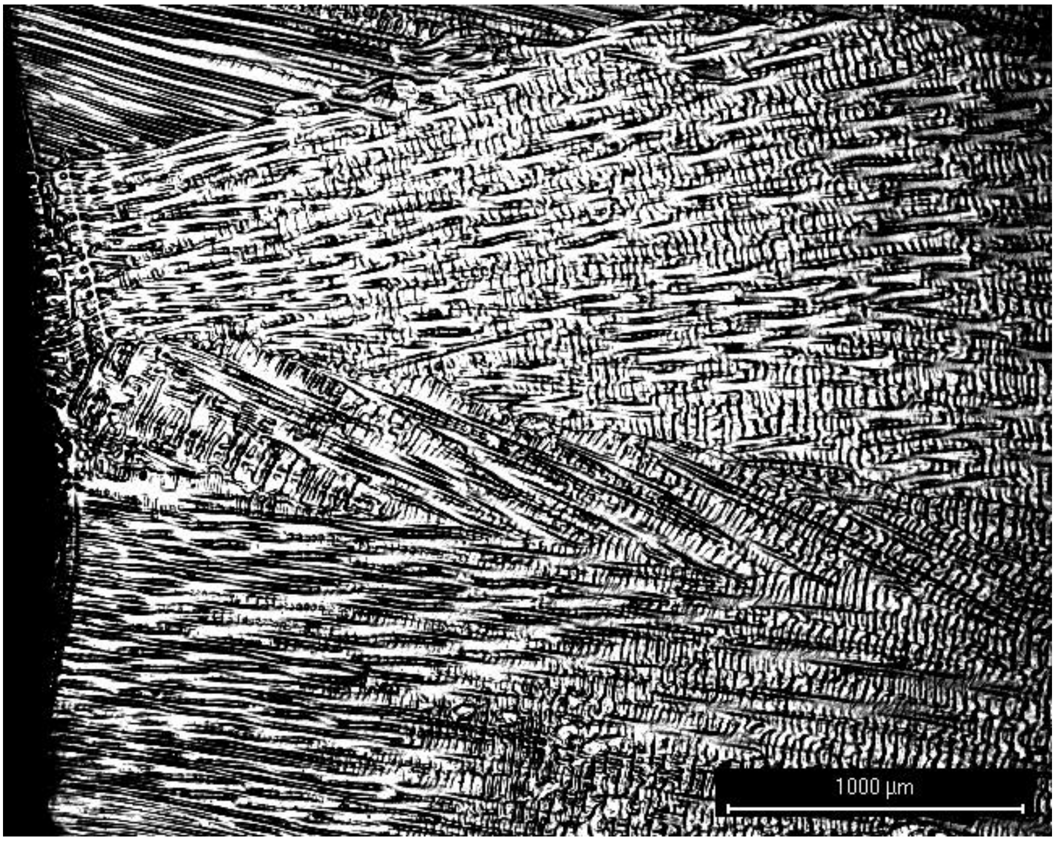

Figure 70. Surface of the stainless steel, fixed mould side, 25X.

Most interesting was that a very marked “band could be found about 4 mm from the surface which is exemplified in Figures 71 and 72 for the soft cooled mould.

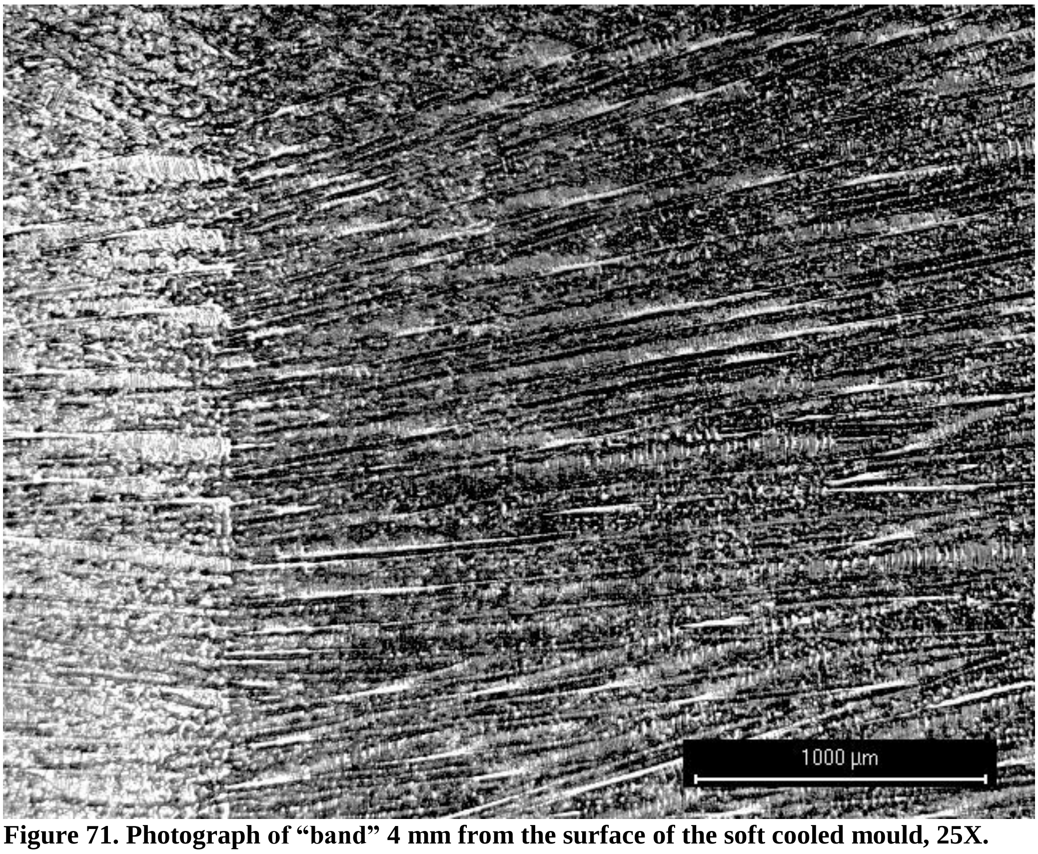

Figure 71. Photograph of “band” 4 mm from the surface of the soft cooled mould, 25X.

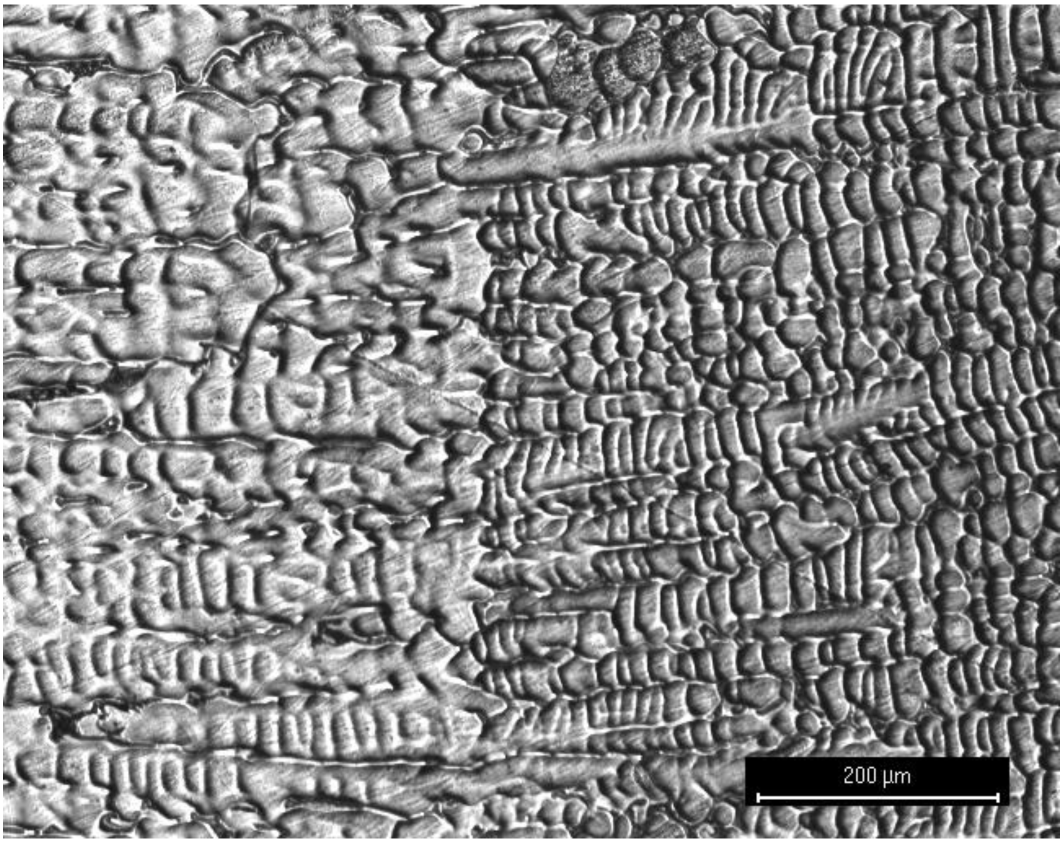

Figure 72. Detailed photo from Figure 71, 100X.

From Figure 70 and 71 it can be noticed that in connection with the “band” there is a marked change in crystal appearance. The crystal changes slightly in direction but they also become finer. A plausible explanation is the following:

- For this casting, with soft cooling mould powder, a low solidification constant about 2.0 could be expected. This means that the “band” is formed about 36 mm from the meniscus according to Figure 69.
- At this region the upward melt flow coming from the SEN will change direction to an inward roll because of inclination with the melt surface.
- The explanation for the change to finer dendrites is due to the fact that this is the position where the slag rim ends which means a great influence of heat flux. This is exemplified by a calculation made by Anders Salwén [ref. 16] in order to exemplify the great influence of heat flux on shell formation shown in Figure 73. The modelling was based on temperature measurements, shown in Figure 74, from two rows of thermocouples in the meniscus area where one row was placed as close as 0.5 mm from the surface.

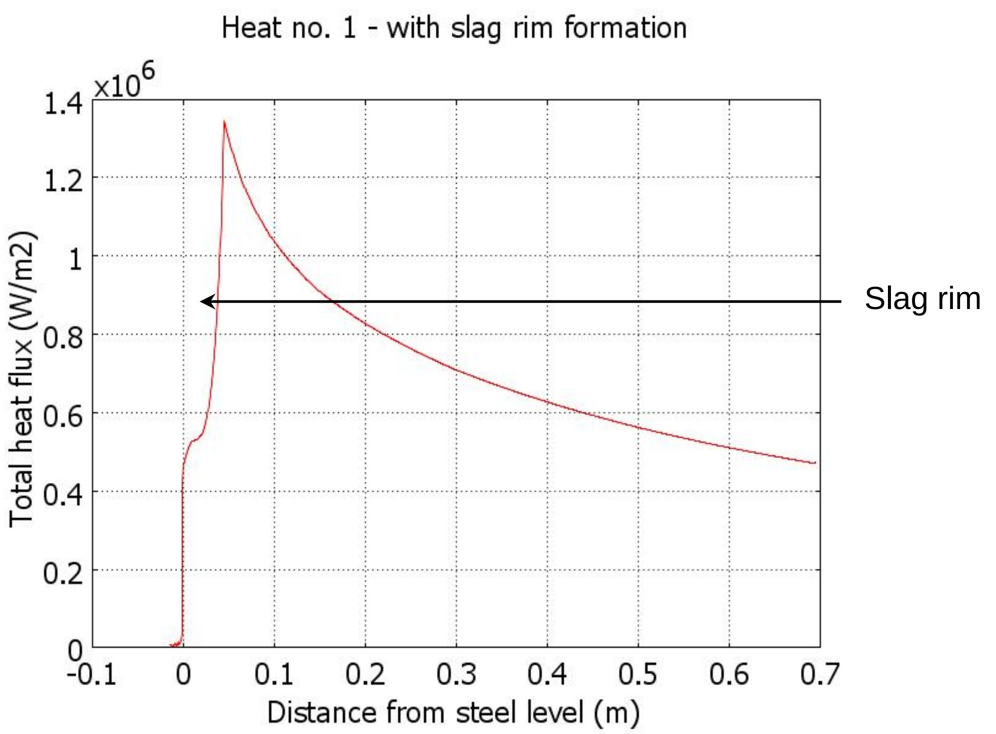

Figure 73. Calculation of heat flux exemplifying the strong influence of the slag rim [ref. 16].

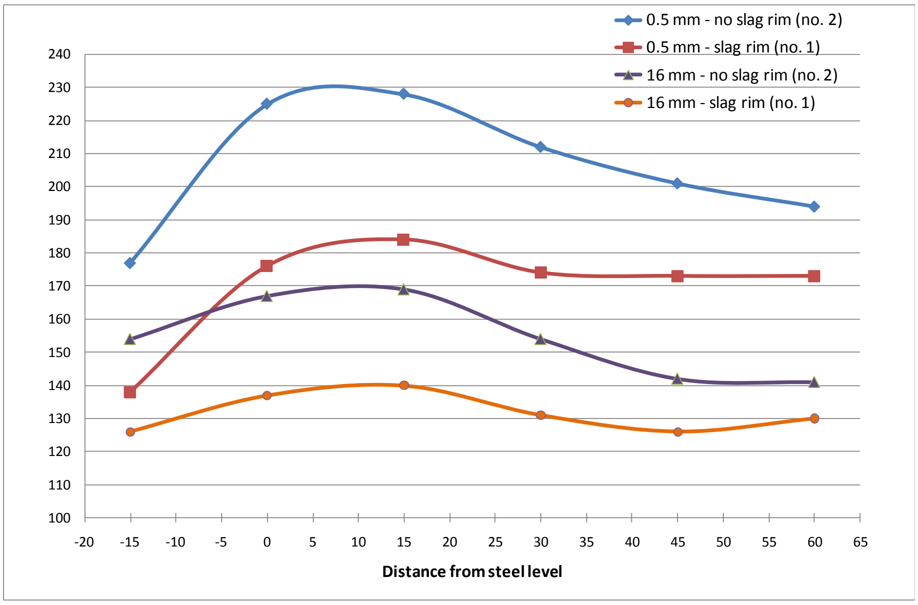

Figure 74. Temperature measurements in the meniscus area, with and without slag rim [ref. 16].

According to this calculation the heat flux is reduced by about 50 % in the area where there is a thick slag rim, which means that this way to reduce the heat flux is a much stronger way compared to the soft cooling by the nickel wedge, which is estimated to be about 20 %.

Due to the very good etching made by Gunnar Logren at Swerea KIMAB it was possible to evaluate the secondary arm spacing in the samples with a result shown in Figure 75 for the fixed mould side.

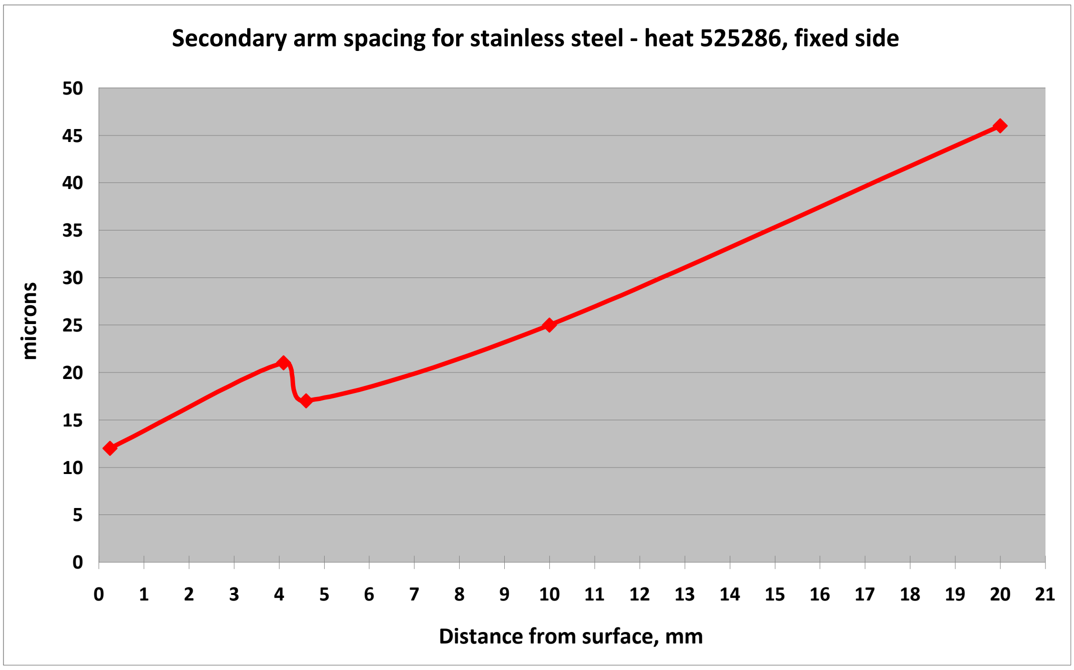

Figure 75. Secondary arm spacing for heat 525286, fixed side.

The secondary arm spacing is a good measure of solidification rate, where a small spacing means a high solidification rate. From Figure 75 it stands clear that the solidification rate increases strongly at a position after the "band".

A comparison of the secondary arm spacing for the soft cooled and the fixed side mould is shown in Figure 76.

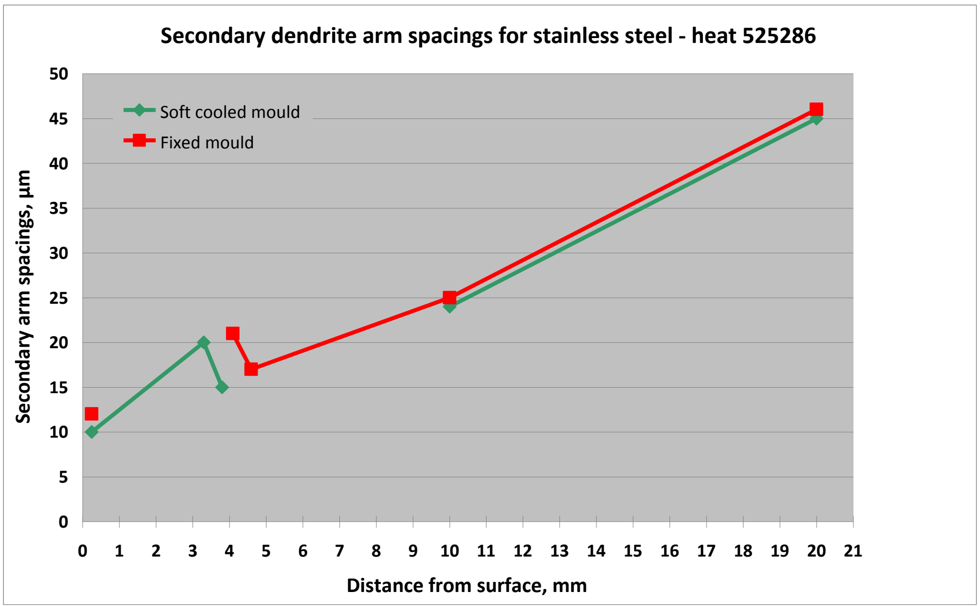

Figure 76. Secondary arm spacing for stainless steel heat 525286.

From Figure 76 it can be concluded that only small differences in secondary arm spacing can be found between the soft cooled and fixed side but that the distance from surface to the "band" is shorter for the soft cooled mould which is an indication of a thinner slag rim which probably is a consequence of the soft cooling.

Another interesting information that could be gained from the metallographic investigation is a second change in dendrite inclination about 12 mm from the surface which is shown in Figure 77. This is probably where the solidification front meets the outlet of the SEN which results in a change in flow direction.

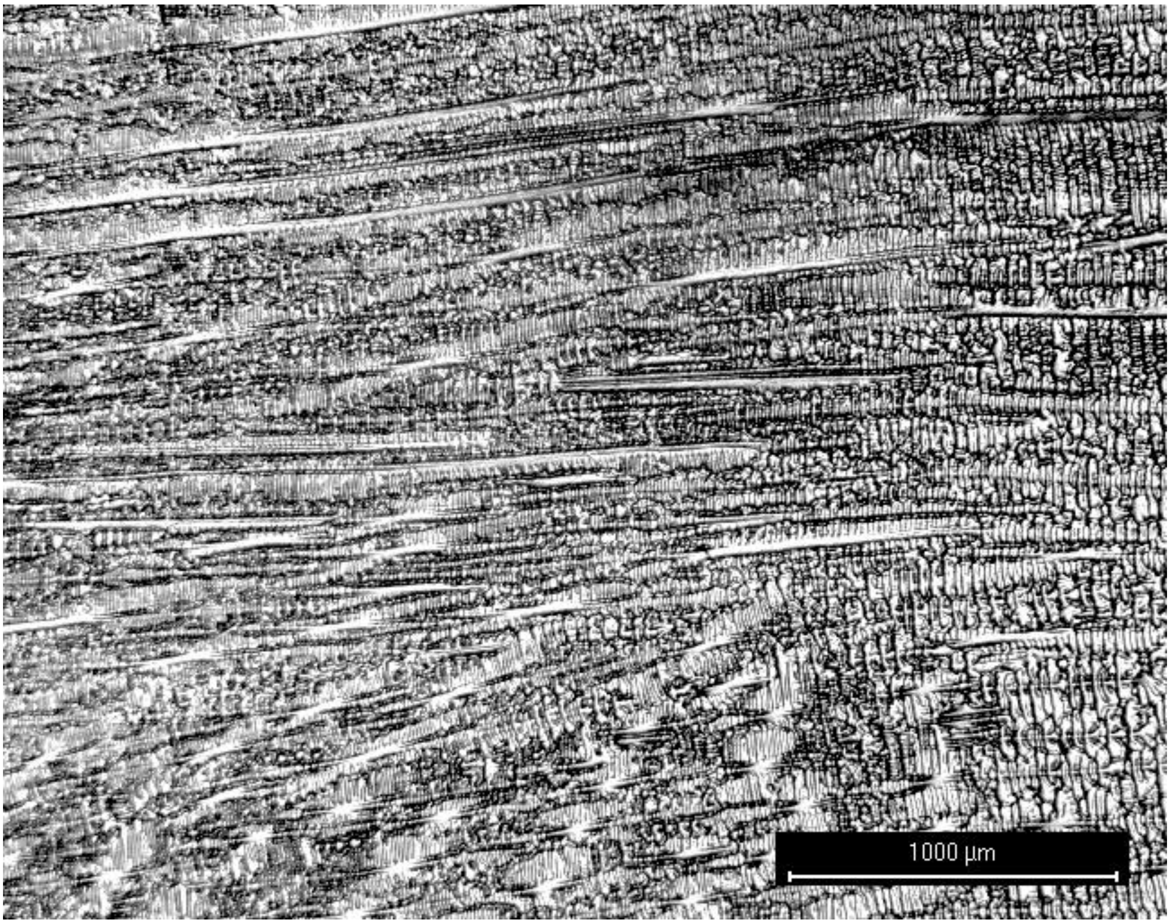

Figure 77. Structure of heat 525286 12 mm from the surface, 25X.

Carbon steel

The carbon steel samples were first nital etched, which did not show the dendrites sufficiently well but showed macro segregation effects clearly. From that is stands clear that the “band” is not only where dendrite crystal change direction but also that there is a white band which reveals negative segregation. This is a proof that there is not only a change in melt flow directions but also an increased flow rate.

To be able to get a better contrast of the dendrites they were etched in agepon. A close examination of the surface showed in this case that the fixed mould had clearly visible “hooks” in connection with every oscillation mark which was not the case for the soft cooled mould. This is exemplified in Figures 78 and 79.

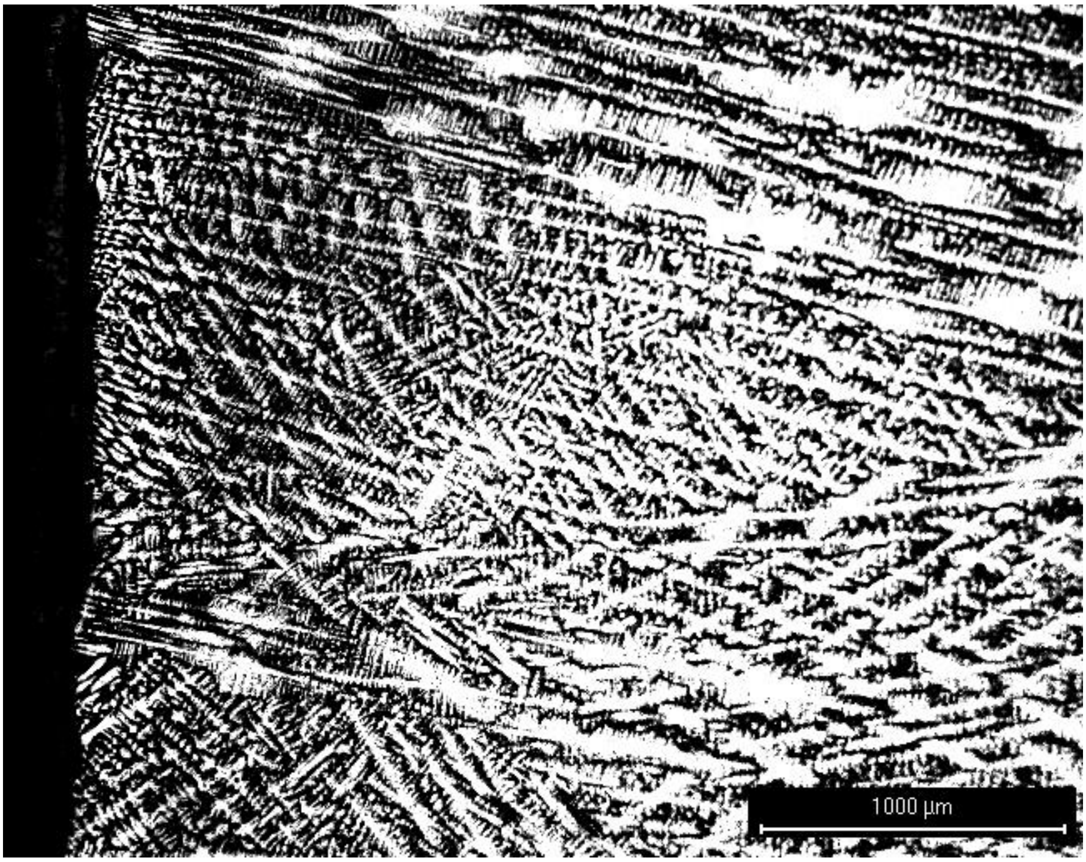

Figure 78. Example of surface for the soft cooled mould without "hook" of 525146-305.

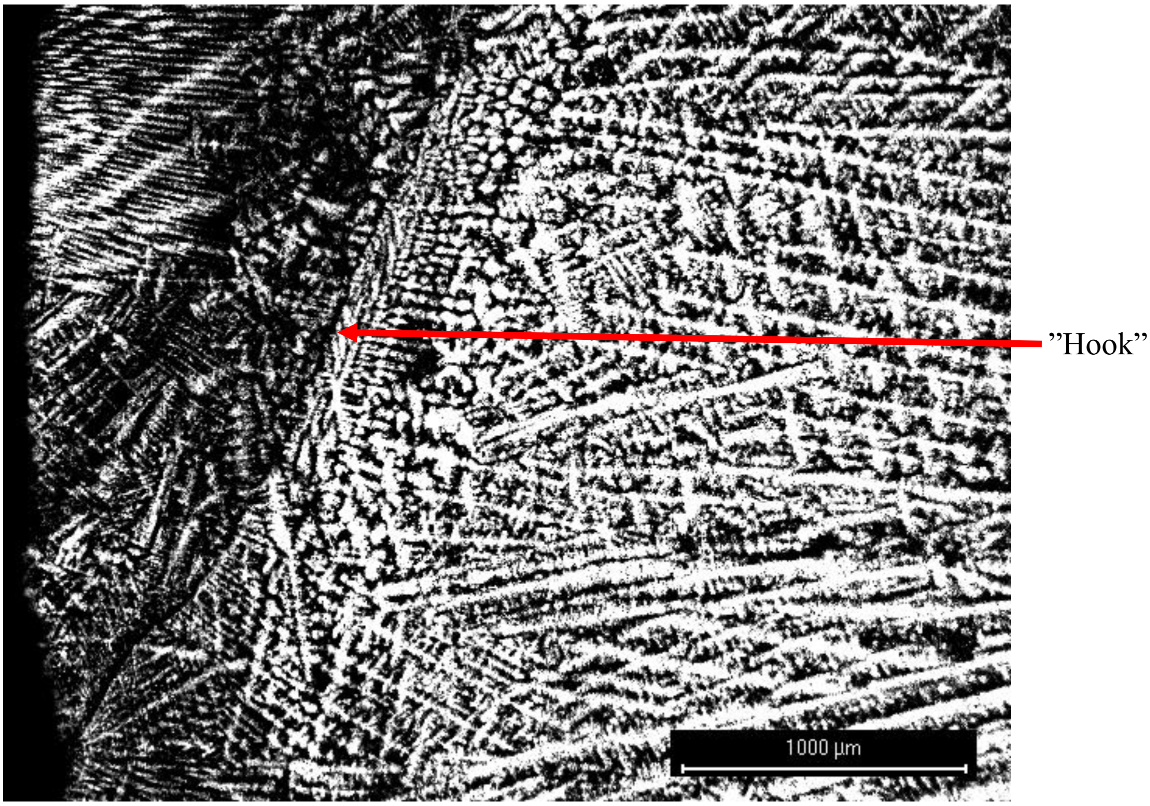

Figure 79. Example of surface area with "hook" for the fixed side of heat 525146-305.

The development of a “hook” in connection with an oscillation mark is an obvious sign of a too strong cooling [ref. 15] of the surface, which is negative for the surface quality while it can act as initiation of surface cracks.

The “band” formation for the carbon steel is shown in Figure 80.

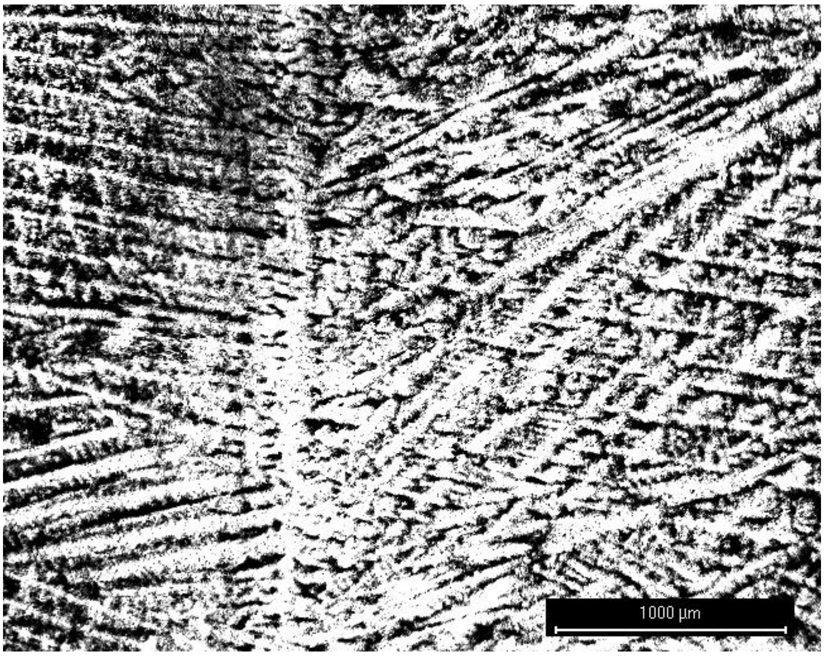

Figure 80. Photograph 4 mm from the surface of the fixed mould for heat 525146-305, 25X.

An evaluation of secondary arm spacing is shown in Figure 81. Due to a very thin slag rim for the used low basicity, amorphous, mould slag no increase in solidification rate could be found but a visible effect of a decline in solidification rate in the “band” area. This is an indication of a slag rim effect also for this mould slag.

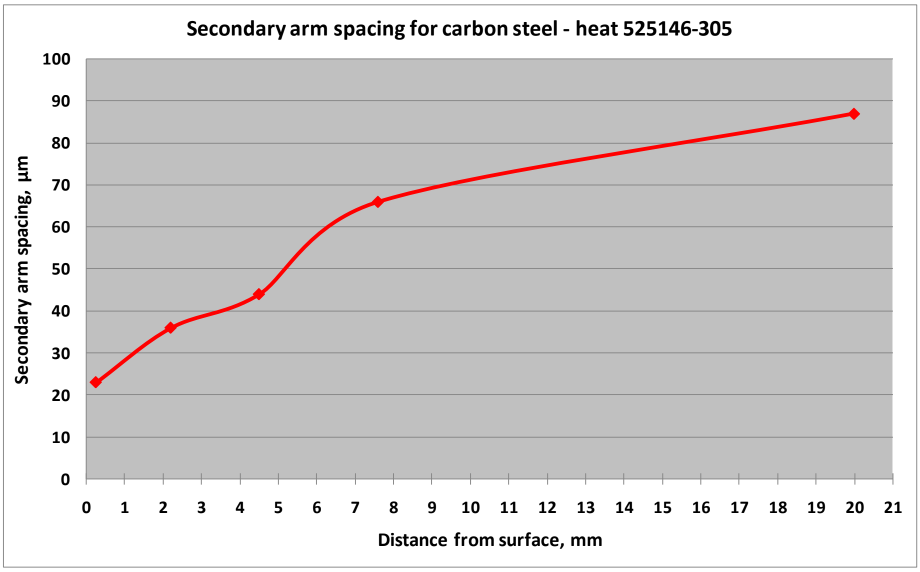

Figure 81. Secondary arm spacing for heat 525146-305 soft cooled mould.

In comparison with the stainless steel in Figure 75 the arm spacing is much wider even if the solidification speed is higher which is because of difference in dendrite formation for stainless and carbon steels.

In Figure 82 a comparison between secondary arm spacing for the soft cooled and fixed mould is made for the carbon steel.

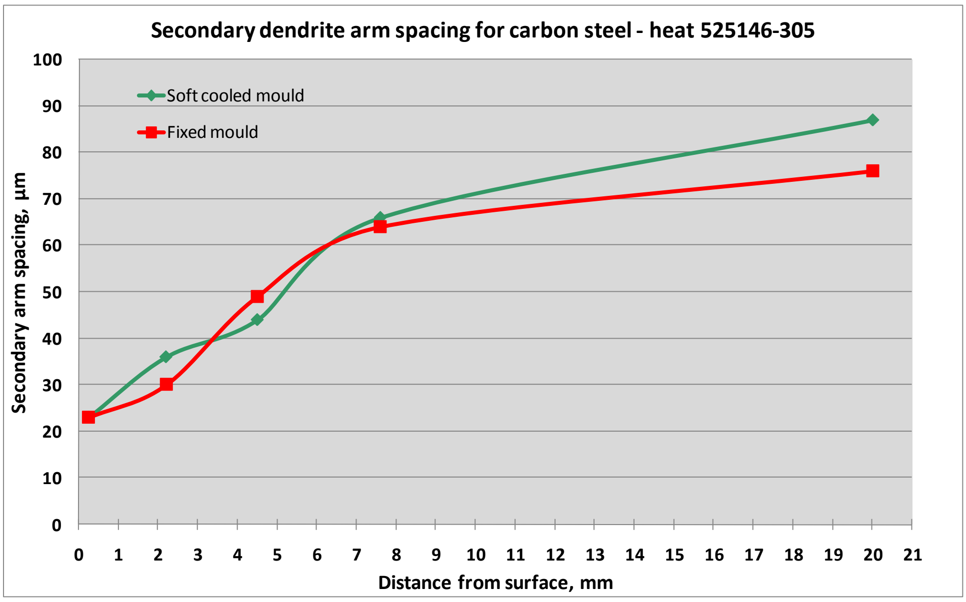

Figure 82. Secondary arm spacing for carbon steel heat 525146-305.

It is difficult to measure secondary arm spacings close to the surface but as a whole it stands clear that the sample from the soft cooled mould have larger secondary arm spacing as a consequence of slower solidification rate.

In Figure 83 the measurements of the distance from surface to the "band" are shown for all studied samples.

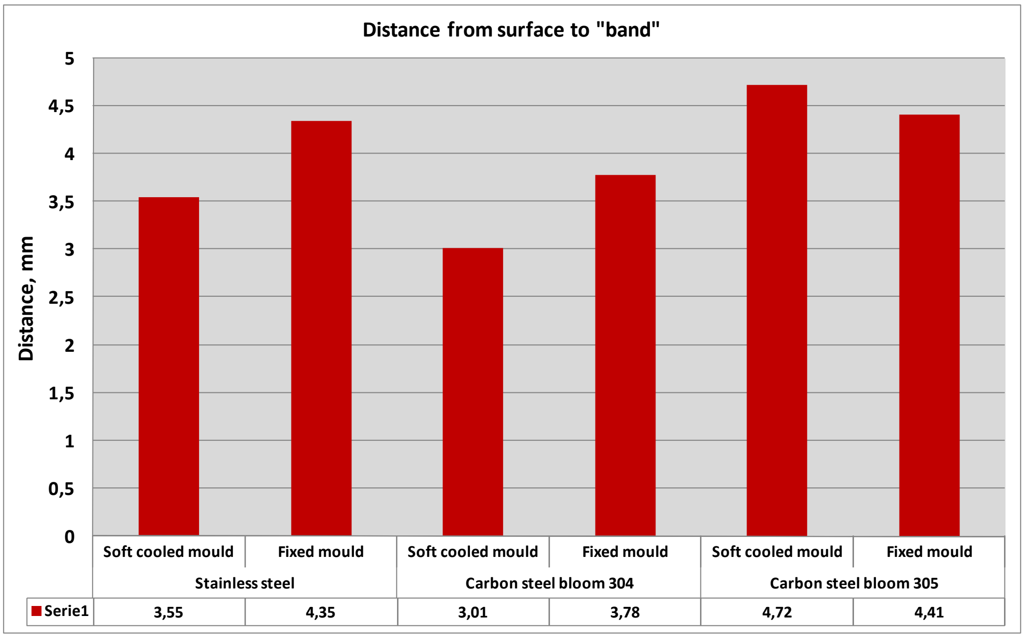

Figure 83. Distance from surface to "band" for stainless and carbon steel.

It is to be expected that the distance to "band" which in reality is the shell thickness should be shorter for the soft cooled mould and this is also the fact for the stainless steel and carbon steel slab no. 304. For heat 305 the distance to the “band” is somewhat shorter for the fixed mould compared to the soft cooled mould, which show the complexity in shell formation. Probably there are variations in the fluid flow from the SEN on the loose and fixed side in this case.

The conclusions from this very limited metallographic investigation are the following:

<u>Stainless steel :</u>

- The soft cooled mould seems only to have a small effect on shell formation for the stainless steel because of the great impact of the thick and wide, highly insulating, slag rim.
- The slag rims strong effect on heat flux is clearly visible by the increase in solidification rate at the position where it ends.
- Beneath the slag rim the slag film is rather thick and partly crystallised which keep a high level of insulation.
- No “hooks” are visible in connection to the oscillation marks neither for the soft cooled nor the fixed mould.

<u>Carbon steel</u>

- The slag rim is small and only partly crystallised.
- Beneath the rim a thin amorphous slag film has been formed with low thermal insulation ability.
- For the fixed mould strong “hooks” can be seen in connection to the oscillation marks which is not the case for the soft cooled mould.
- For this case the soft cooled mould has a clear bigger impact regarding the initial solidification.

5. Bonding technique for soft cooled layer

A full scale CC-production with soft cooled mould is fully dependent on the possibility to manufacture a soft cooled layer with the same service life as the copper mould itself. Of that reason much effort has been spent, within the project, to build competence regarding bonding technique for the soft cooled layer. This was done by thorough investigations of the soft cooled layer after the experiments in the steel plants where gradually more and more knowledge were achieved.

5.1 Bonding technique for experiment at SSAB EMEA Oxelösund

Based on the design criteria described in chapter 3 the stainless steel 253 MA was chosen for the soft cooled layer for the trial in Oxelösund because of its superb high temperature properties. Based on long time experience in Oxelösund a welding of stainless steel against a copper mould needed a bonding layer consisting of 2 mm of nickel. The chemical composition of the nickel welding material is shown in Table 17.

Table 17. Chemical composition of Nickel welding material, wt-%.

Ni+Co	Ti	Mn, max.	Fe, max.	Si, max.	Al, max.
93	2.0 – 3.5	1.0	1.0	0.75	1.5

5.1.1 Welding method

Leif Eklund at the workshop in Oxelösund gave the following information regarding the welding technique of the soft cooled layer.

The starting Ni-layer is welded manually with a TIG welding. Thereafter the welding is made with pin electrodes using an old Miller equipment with high current, 800 Ampere, the first layer with 2.5 mm electrode and the rest with 3.2- 4 mm electrodes. To avoid the mould to bend during the welding operation, because of the thermal tensions, it must be screwed against a thick steel plate which is shown in Figure 28.

5.1.2 Chemical composition of the weld material

With this mould totally 46 heats were cast at the continuous casting line in Oxelösund with a total amount of 9200 tons of steel corresponding to a production time of 53 hours. After the trials the mould was sent to Swerea KIMAB for investigation.

At Swerea KIMAB two samples were taken out for analysis of the chemical composition with GDOES (glow discharge optical emission spectroscopy). Before the analysis 2 mm of the surface was milled away to remove the chromium surface and possible impurities. The results from two analyses are shown in Table 18. The compositions from the suppliers are shown and a complete composition from an earlier investigation at Swerea KIMAB [ref. 17].

Table 18. Chemical composition for 253 MA, wt-%.

Element, wt -%	Product sheet 253 MA pin electrode	Sample, no.1	Sample, no.2	Chemical composition from ref. 5
C	0.08	0.094	0.119	0.086
Si	1.5	1.167	1.273	1.70
Mn	0.7	0.828	0.773	0.59
P		0.022	0.029	0.022
S		0.010	0.014	0.001
Cr	22	22.57	22.54	20.97
Mo		0.18	0.19	0.17
Ni	10.5	14.19	13.90	10.98
Al		0.016	0.016	0.013
N	0.18	0.049	0.049	0.152
Cu		7.57	6.55	0.27
Ti		0.021	0.017	0.007
Nb		0.027	0.031	0.007
Co		0.056	0.060	0.14
Ce		0.088	0.044	0.038

Comments:

- The bonding layer of Ni has partly mixed with the weld of 253 MA and increased the Ni-content with about 3.5 wt-%
- In spite of the Ni barrier high amounts of Cu (about 7 wt-%) has been alloyed in the weld material of 253 MA.
- The N-composition has been strongly reduced by the welding operation, only 27 % is remaining.
- The Ce-composition has been reduced with 50 %.

5.1.3 Results from macroscopic investigation of the welding material

In a region of about 50 mm width severe cracks have emerged, which is shown in Figure 84 from a photo which is taken from the mould surface.

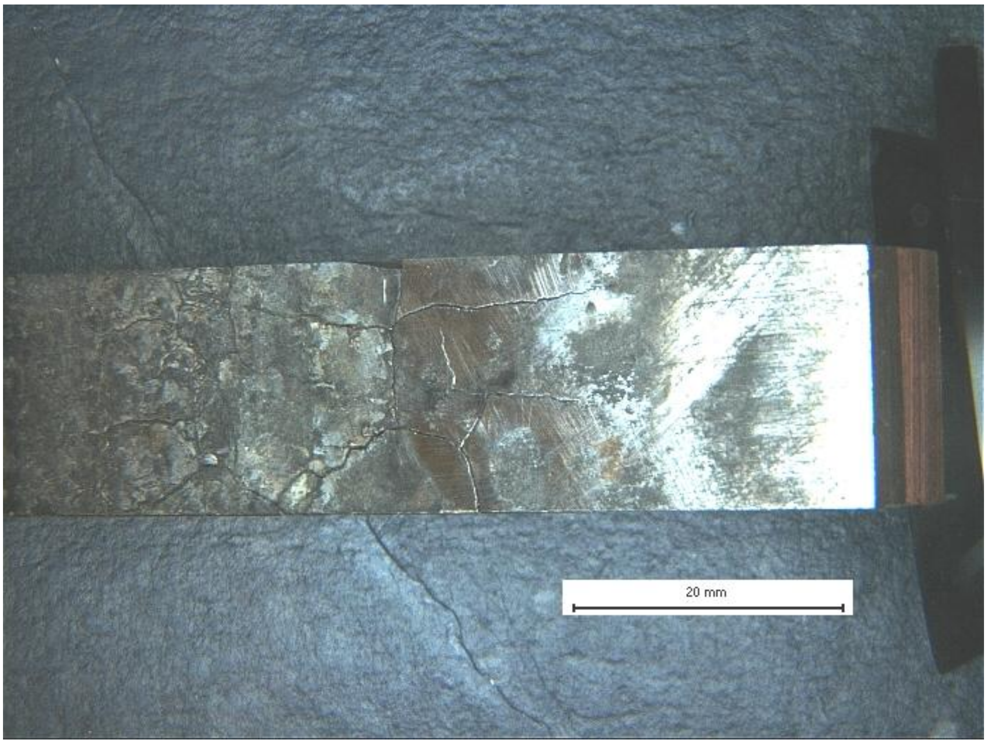

Figure 84. Photo from the surface of the soft cooled mould, 2X.

In Figures 85 and 86 a cross section from the weld is shown at two magnifications.

Figure 85. Photo from cross section of the weld at the lower part of the welding, 2X.

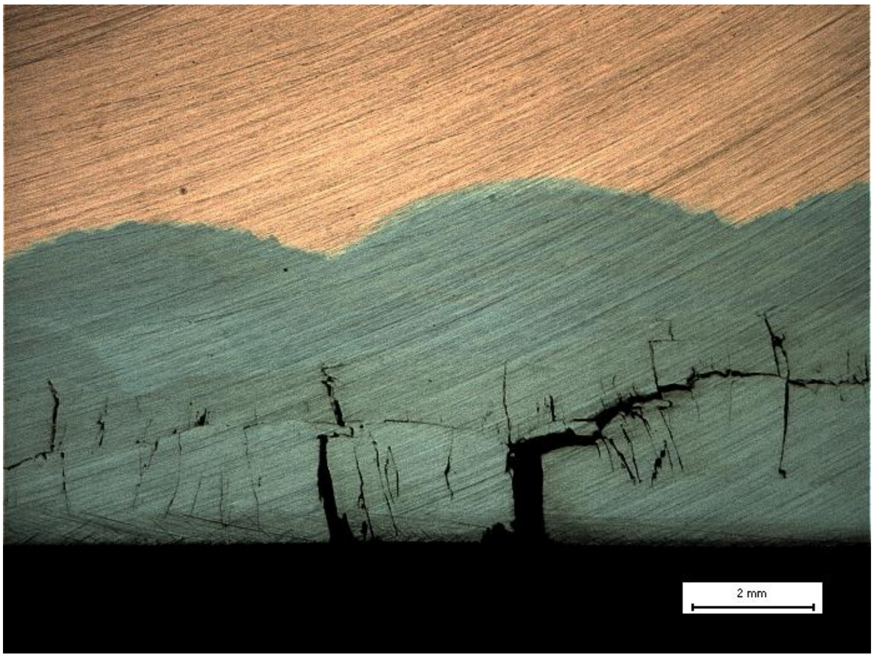

Figure 86. Detailed photo from cross section of the weld 55 mm from steel meniscus, 10X.

Conclusions:

- No lamination between mould and weld material could be found.
- The thickness of the weld was only 6-7 mm instead of the planned 8.5 mm.
- No cracking in the nickel weld.
- The cracks seem to start in the layer between Ni and 253 MA and was spreading upwards.

To get a better understanding of the propagation of the cracking in the weld the mean temperature 10 mm from surface is shown in Figure 70 together with a drawing of the soft cooling wedge. The temperature is based on the temperature logging during the experiments for heat no. 46176.

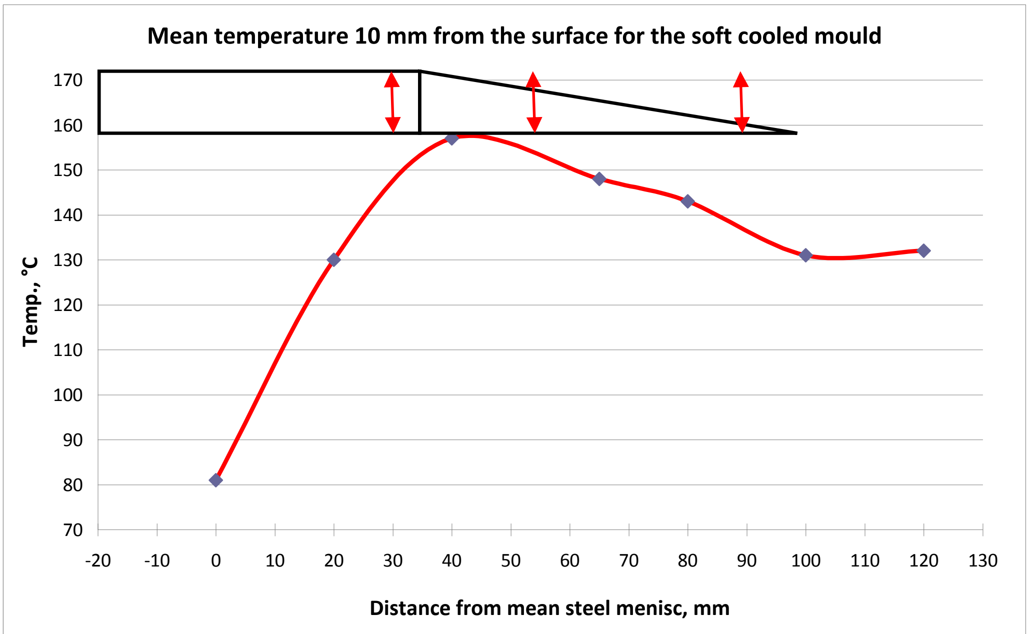

Figure 87. Mean temperature for soft cooled mould for heat 46176.

In the figure three vertical arrows are drawn, the first where the cracks first emerge (30 mm from mean meniscus level), the second where the cracking is at its maximum (55 mm from meniscus) and finally the third 90 mm from meniscus where the cracking end. The explanation to why the cracks do not start at the meniscus is the fact that the mould temperature in this position is low due to the cooling from the upper part of the mould without steel contact (see Figure 7). The reason that no cracks appear at the lower part of the mould is that the weld in this region only consists of nickel. Another positive factor is the lower mould temperature.

5.1.4 Results from metallographic investigation of the weld with LOM (light optical microscope)

The polished samples were etched with aqua regia at 75 °C. A photo from the contact area between Ni and 253 MA is shown in Figure 87.

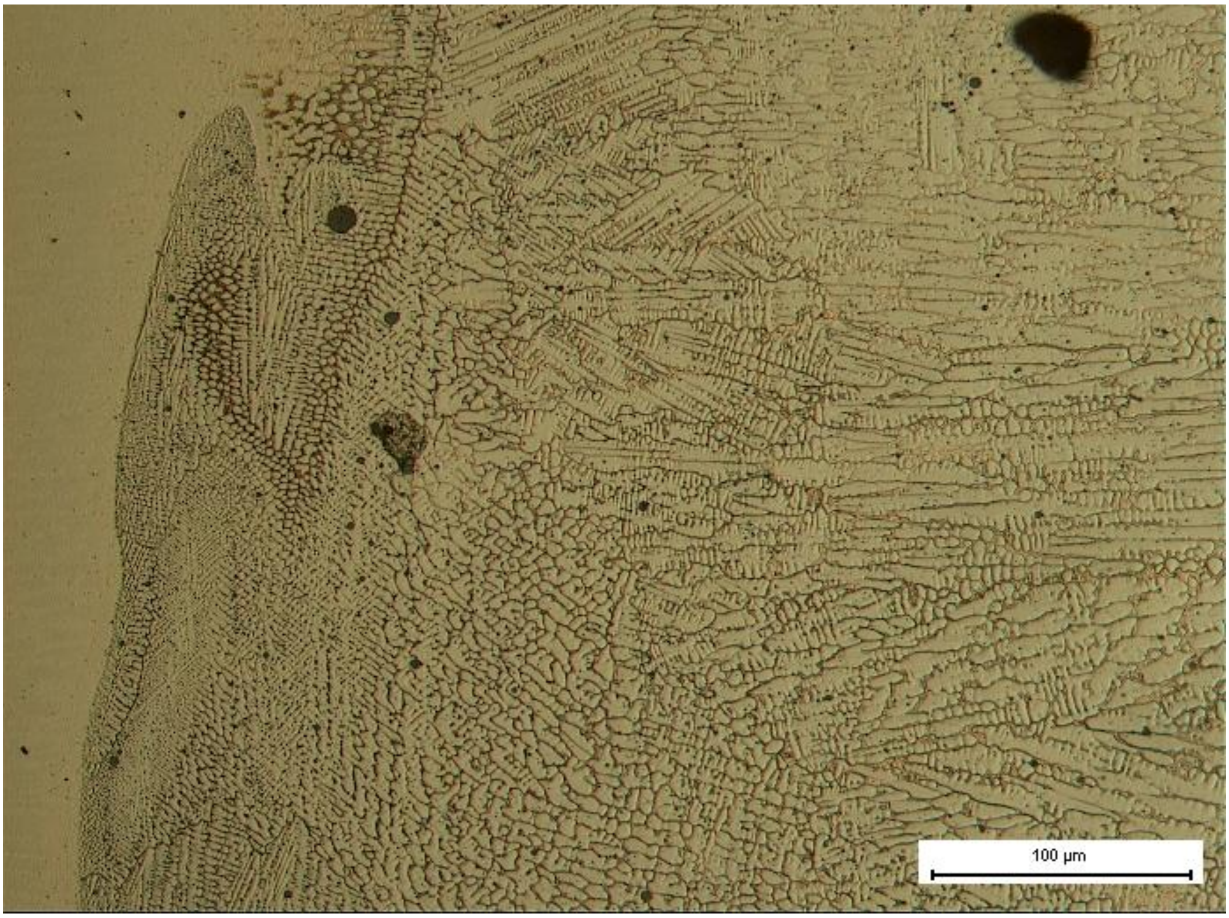

Figure 87. Contac area between Ni-layer and 253 MA, 200X.

In Figures 88 and 89 photos with different magnification is shown from a cracked area.

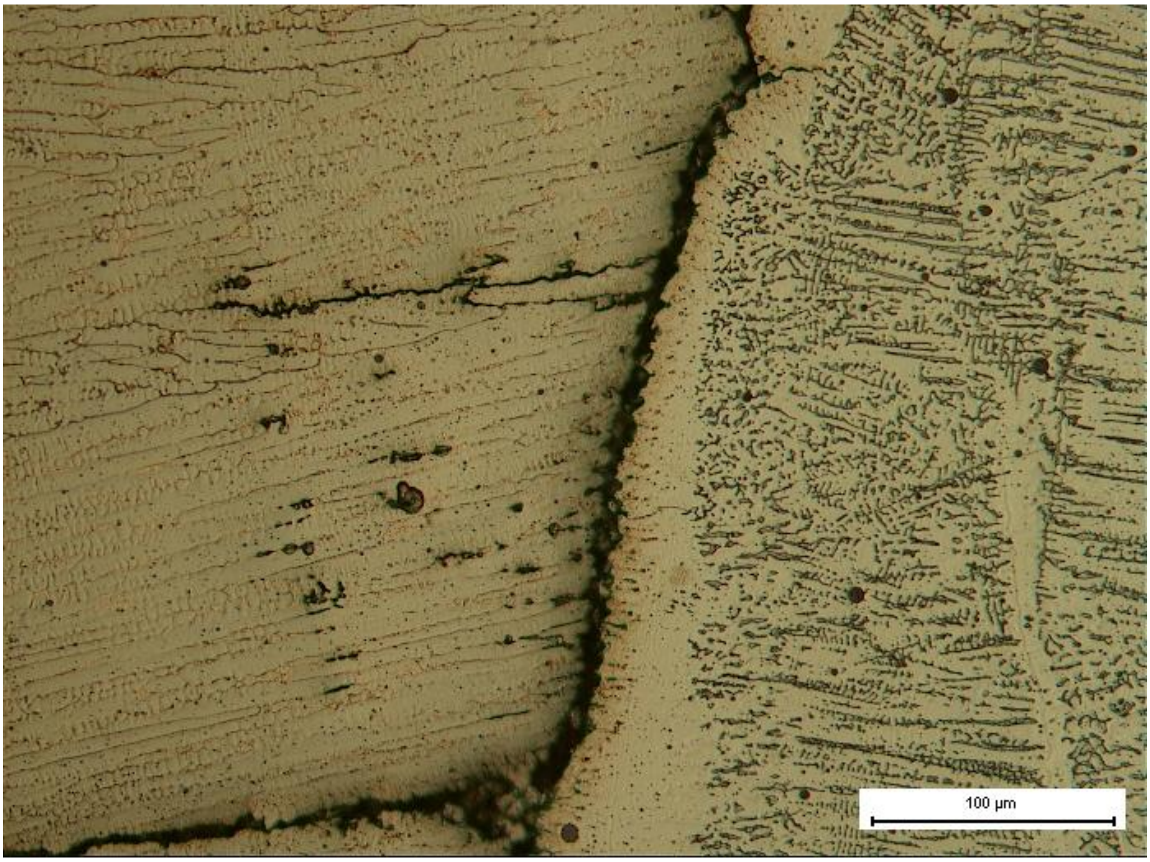

Figure 88. Bonding zone between two welding layers with cracking, 200X.

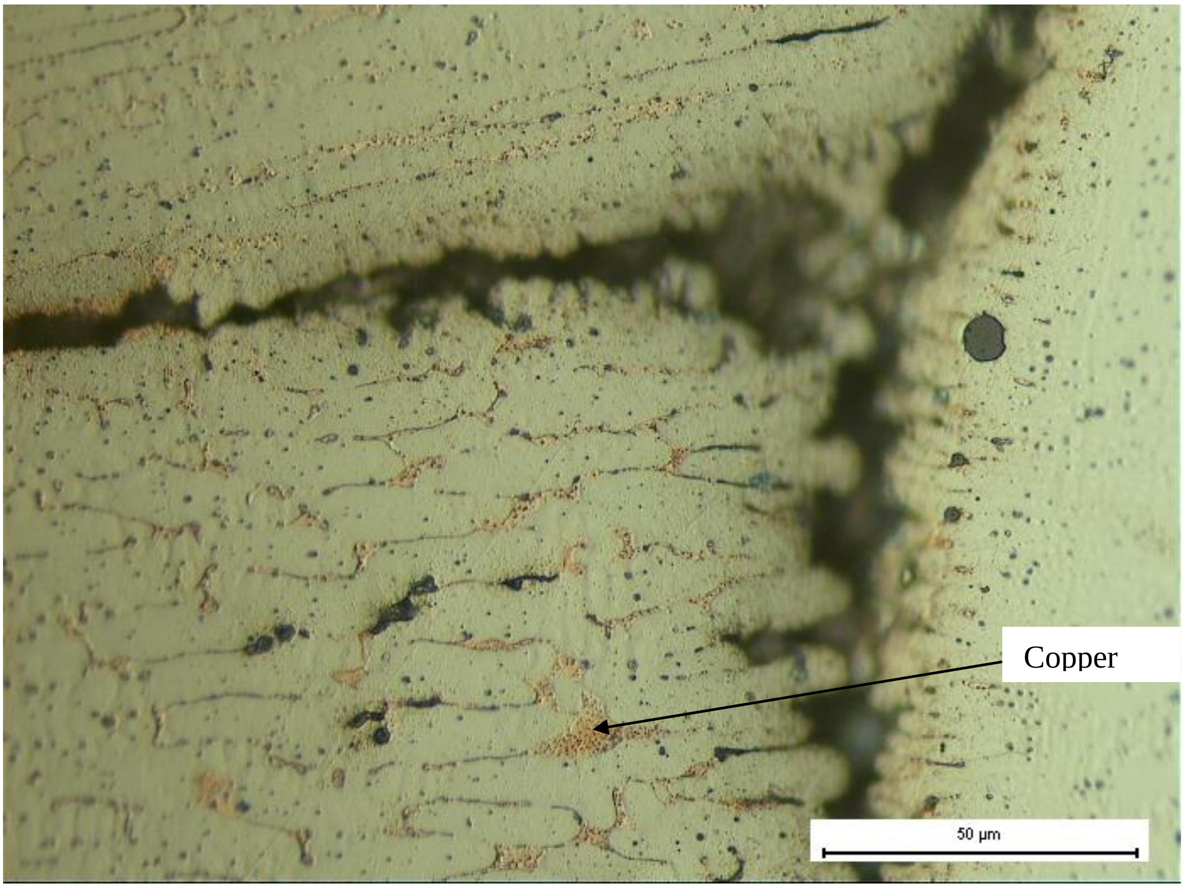

Figure 89. Bonding zone between two welding layers with cracking, 500X.

Conclusions:

- The soft cooled layer became thinner than planned, about 6-7 mm compared to 8.5 mm.
- The reason for the cracking is due to a high Cu-content in the stainless steel. Due to the low solubility of Cu in steel the copper will segregate during solidification and remain as copper between the dendrites, thus causing hot shortness due to high surface temperature in the surface in connection with strong tensions caused by thermal stress.

5.3.4 Bonding technique for experiments at Sandvik Materials Technology

Nickel has a very good solubility of copper and, as has been seen from the trials in Oxelösund, is not sensitive to hot shortness. The reason for not using nickel in the first place for the experiment in Oxelösund was the fact that Ni is expensive and has a rather high conductivity, 91 W/m,K for pure Ni. The weld material itself is though alloyed with Ti and Cu is mixed with the Ni during the welding operation so the nickel is by far to be pure. From earlier investigations at Swerea KIMAB [ref. 18] it became clear that the thermal conductivity is strongly decreased when a metal is alloyed. To investigate the true conductivity of the welded Ni a sample was taken out from the used mould from Oxelösund and a test was made by Peter Andersson with Swerea KIMAB's hot disk equipment. The samples for the test are shown in Figure 90 and the result from the investigation in Figure 91.

Figure 90. Samples for investigation of thermal conductivity with hot disk.

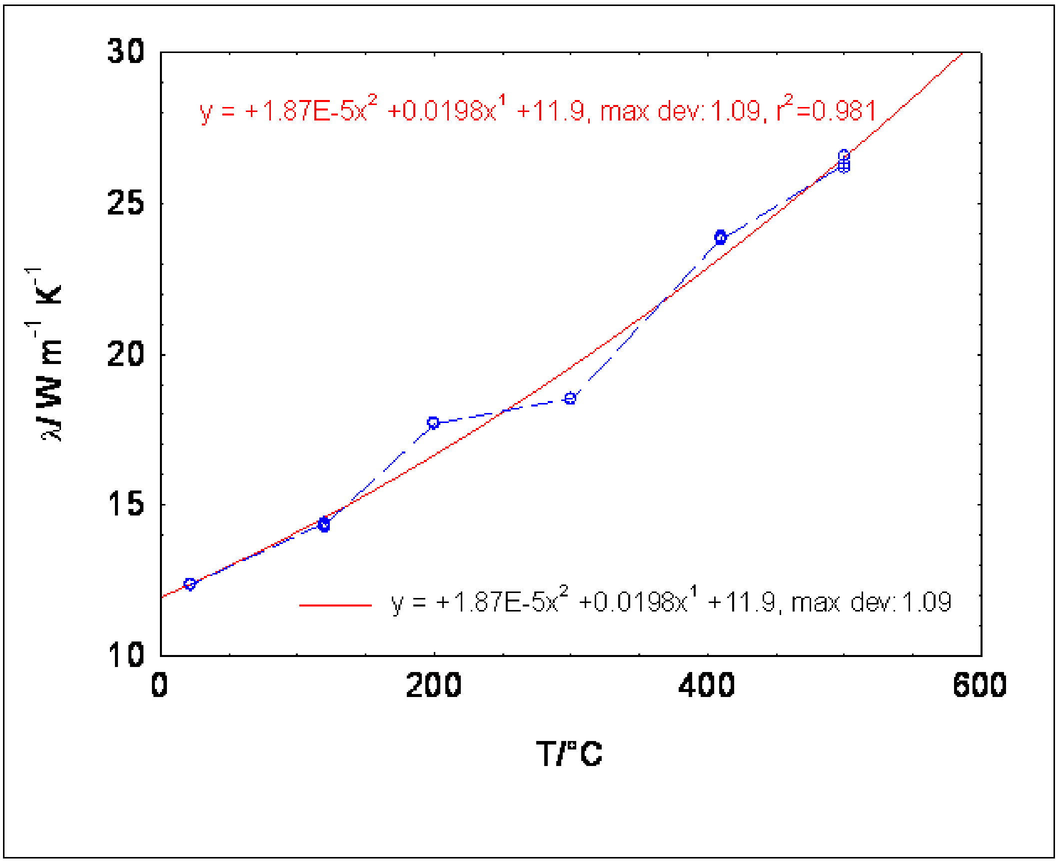

Figure 91. Results from hot disk evaluation of welded Ni-layer.

As can be seen from Figure 91 the result was very promising why it was decided to make the welding for the trials in Sandviken solely with nickel. It was also decided to compensate for the milling in order to achieve a final thickness of the soft cooled layer of 8.5 mm. The welding was done with the first layer with TIG and the rest with pin electrodes.

The trials in Sandviken were limited to six heats with a total of 600 tons of steel. After dis-section of the mould at Swerea KIMAB no cracks could be found in the Ni-wedge which is exemplified in the cross section shown in Figures 92 and 93.

Figure 92. Cross section of the soft cooled mould in Sandviken.

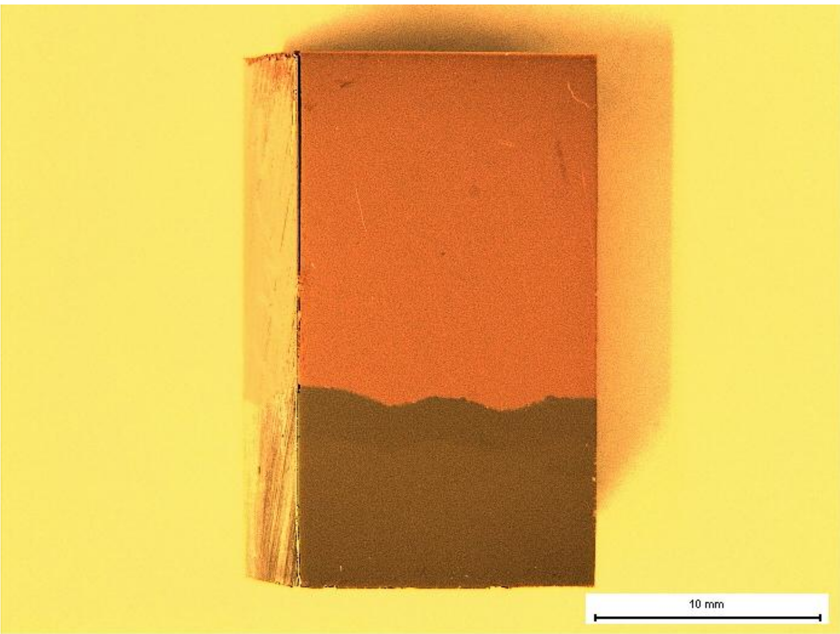

Figure 93. Macro photo of cross section with Ni weld.

In Figure 94 a LOM photo of the bonding region is shown.

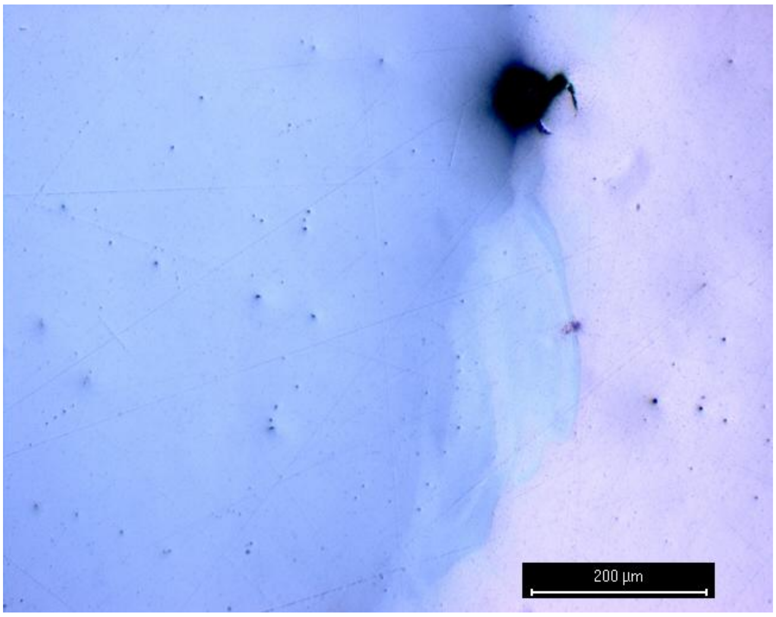

Figure 94. LOM picture from the bonding region, 100X.

Figure 94 shows that a good bonding between Ni and the Cu mould has taken place except from one large micro porosity. Small shrink porosities from the welding can also be seen and also micro porosities in the copper which seem to consist of copper casting.

In figure 95 a SEM-picture of the bonding is shown.

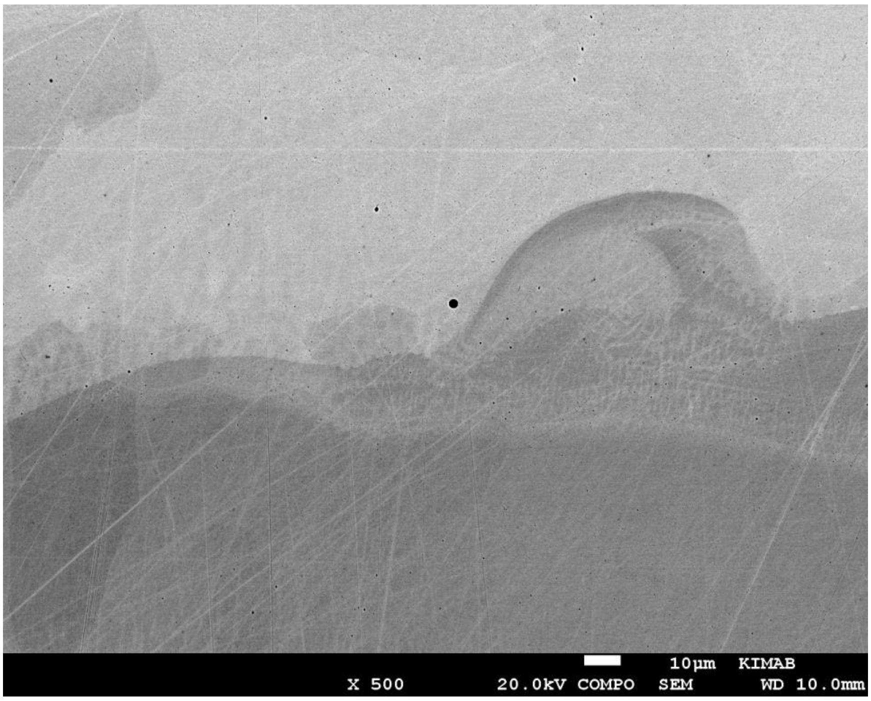

Figure 95. SEM picture of the bonding, 500X.

The SEM-investigation was made to investigate the Cu-infiltration in the Ni-layer.

The result from this investigation is shown in Figure 96.

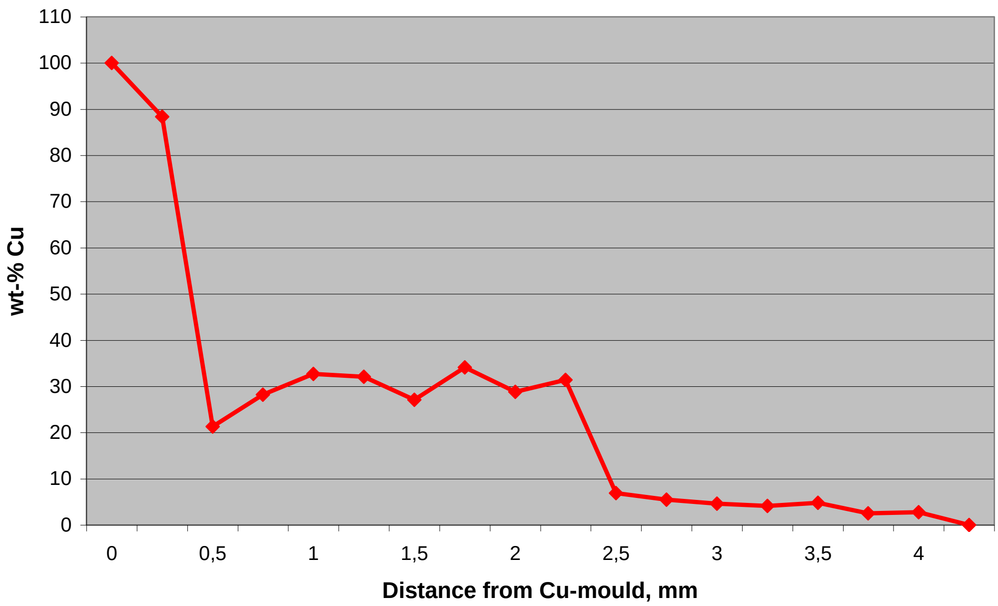

Figure 96. Cu-infiltration in Ni-weld

From the information in Figure 96 there is no mystery that the soft cooled layer in Oxlösund suffered from hot shortness. It stands also clear that the Ni layer will have a low thermal conductivity which is beneficial for its function as thermal barrier.

5.3.5 Bonding technique for experiments at Outokumpu Stainless Avesta

The soft cooling with a welded Ni layer seems to have potential to be a method with good function regarding thermal properties and long service life. The method has though two large disadvantages which could jeopardize its future industrial usefulness:

- The manual welding operation is very slow and because of that costly. The welding of the relative small mould for SMT was a full time work for a welder in two days.
- Nickel is a very expensive metal.

For that reason it was in decided already in October 2008 to investigate an alternative method for the preparation of the soft cooling. This was done with the help of Tag Hammam, who was working at Swerea KIMAB with a project called "Cold spray". With this method a powder is sprayed against a thoroughly cleaned surface through a Laval nozzle at twice the speed of sound. This method is rather quick and gives a narrow mixed zone. At the project meeting No.11 it was decided to make a preliminary trial with stainless steel powder on a copper sample at the Helmut Schmidt University in Germany.
At that trial two layers were sprayed, 3 mm and 10 mm thick from where a cross section is shown in Figure 97. From this trial we also learned that the designation "cold spray" is not exact when it comes to metals with high melt temperature. Warm or hot spray is a better word since the powder had to be pre-heated to about 600 °C.

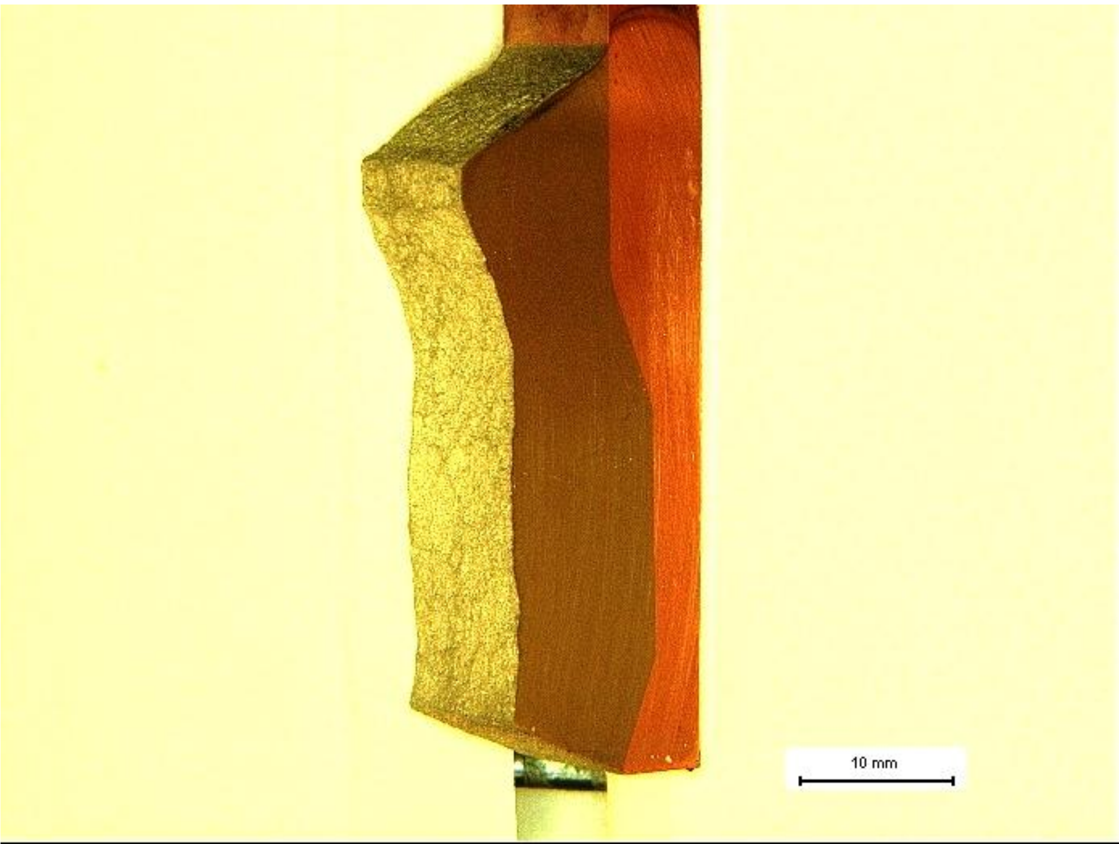

Figure 97. Cross section of a "cold sprayed" layer of stainless steel on copper.

A SEM-study revealed a good bonding but a large amount of micro porosities which is shown in Figure 98.

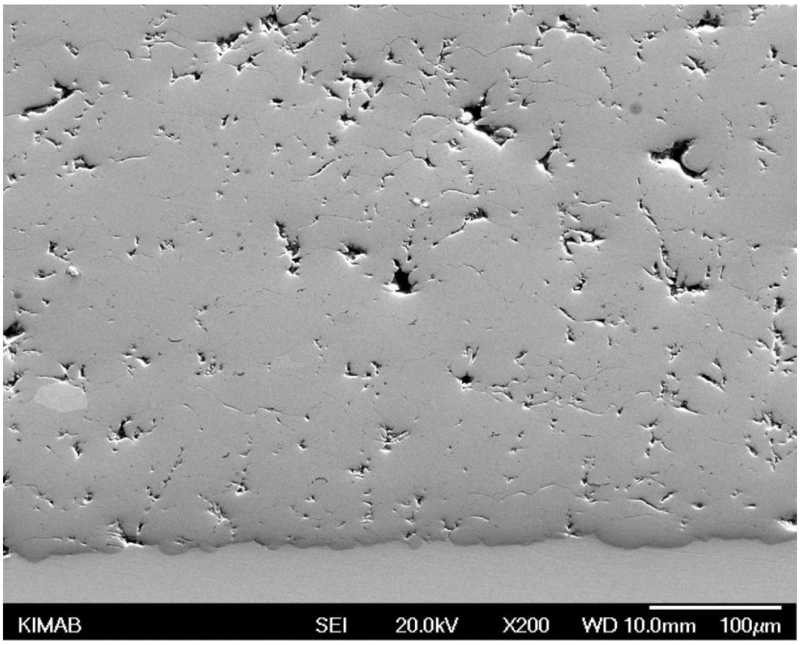

Figure 98. Bonding area with cold sprayed stainless steel against copper, 200X.

A line analyze proved that a good bonding had been achieved with a short infiltration of copper which is shown in Figure 99.

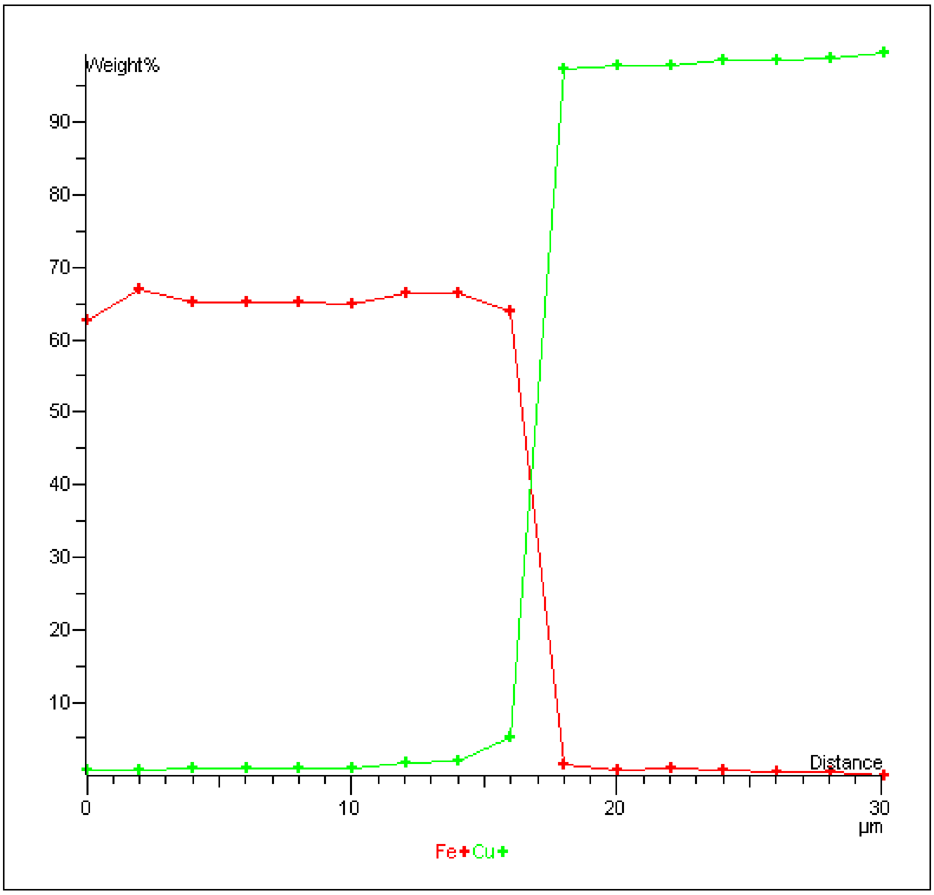

Figure 99. Chemical composition of Fe and Cu in the bonding zone.

Conclusions:

- A good bonding has taken place with a thin zone mixed with Cu and Fe.

- The infiltration depth of Cu is only about 5 µm compared to 4 mm with traditional welding.

The size of the porosities was rather large but with a good bonding between the steel powders it was considered to be worth a full scale trial. To do this with a minimum of risk it was decided to make the trial on a narrow side at Outokumpu Stainless in Avesta.
A mould was sent to Swerea KIMAB where the milling for the soft cooled layer was made.

The Helmud Schmidt University was operating very slowly and thus it was decided to change to a new company for the manufacturing of the “cold spray”. The company GfE in Freiberg was contracted for the work. It showed not to be an ideal partner who worked very unprofessional. We had to delivera special powder from Höganäs (grade 310B) with narrow limits regarding grain size. At Freiberg the powder had to be screened a second time before the spray operation. After more problems with the operation, where the mould was sent to Stockholm again for milling after an unsuccessful trial, we had to send Tag Hammam to Germany to supervise the process. It turned out that they could only spray some mm with stainless steel because of practical problems, therefore the top surface had to become nickel. The final soft cooled layer thus consisted of three layers, Ni – stainless steel – Ni.

After the cold spray coating the mould was sent to Swerea KIMAB for milling, where it was found that the corners of the surface were rounded, which made it necessary to send the mould to Oxelösund for welding of this part, where finally after a new milling the mould was sent for chromium-plating.
After all this work it was only possible to cast one heat with this mould in Avesta under the supervision of Jesper Janis, which was a disappointment because the original plan was to cast at least 20 heats. The reason for this was that the surface had a large number of cracks while it had to be taken out of operation and was sent to Swerea KIMAB for dissection. In Figure 100 a photo from the strongly cracked surface of the soft cooled mould is shown.

Figure 100. Photo from mould surface.

In Figures 101 and 102 two macro photographs are shown from the cross section.

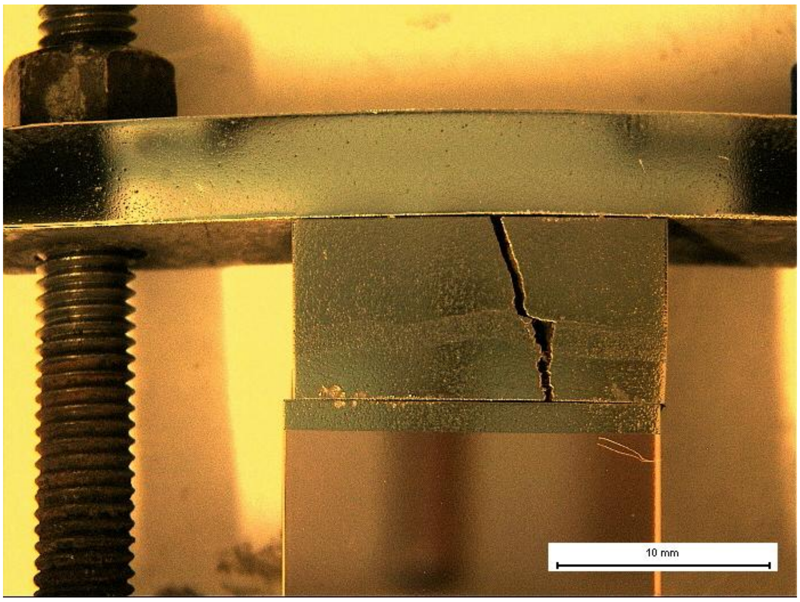

Figure 101. Photo from cross section of the soft cooled layer.

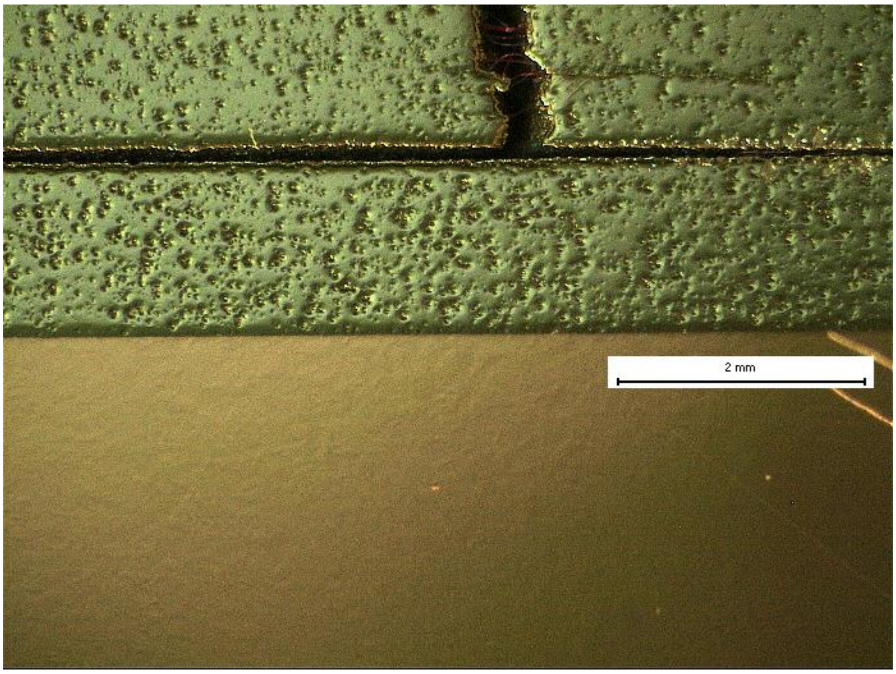

Figure 102. Photo from cross section.

From the photos it is clearly seen that the second cold spray operation has been very bad. No bonding has taken place between the milled layer from the first cold spry operation and the second. Very large porosities can be seen especially in the stainless steel layer.

A thorough investigation of the bonding between mould and the first cold-sprayed Ni-layer revealed that this has been successful which is shown in Figure 103 from a LOM examination.

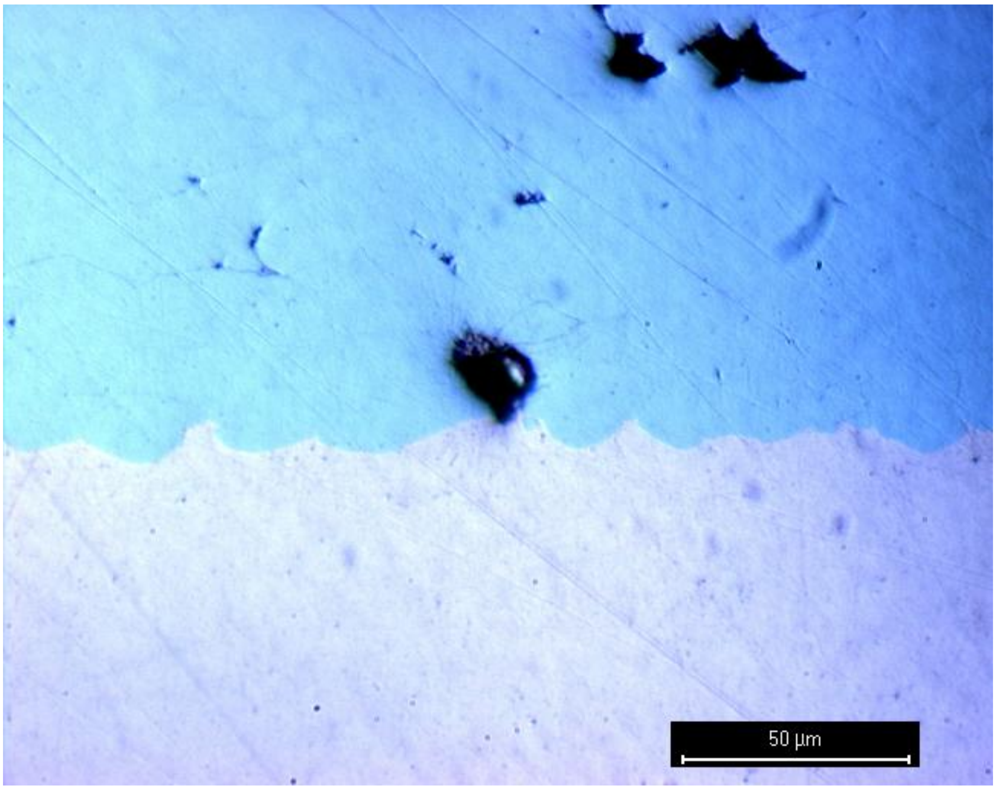

Figure 103. LOM photo from the bonding area from the cold sprayed mould, 400X.

From the LOM study it was obvious that the bonding and degree of porosities from the second cold spraying operation was unacceptable resulting in a very poor strength, Figure 104.

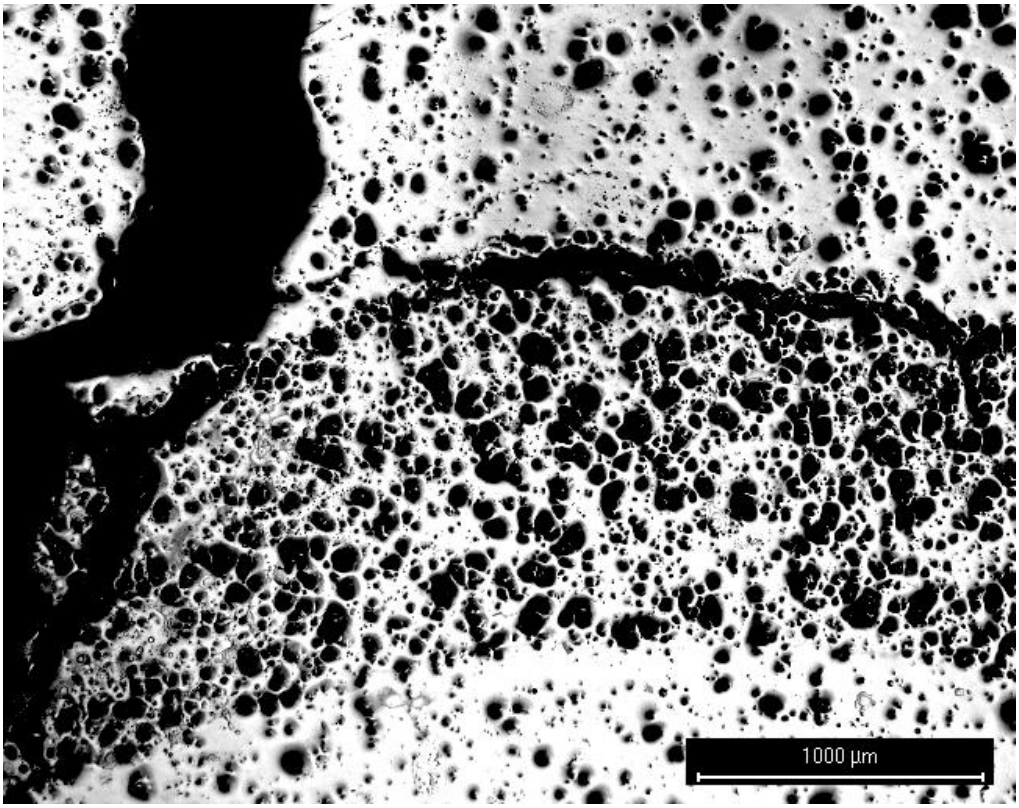

Figure 104. Photo of cracked area with stainless steel, 25X.

This is further visualised from the SEM-photo in Figure 105 where it is obvious that the bond between the steel particles is very poor.

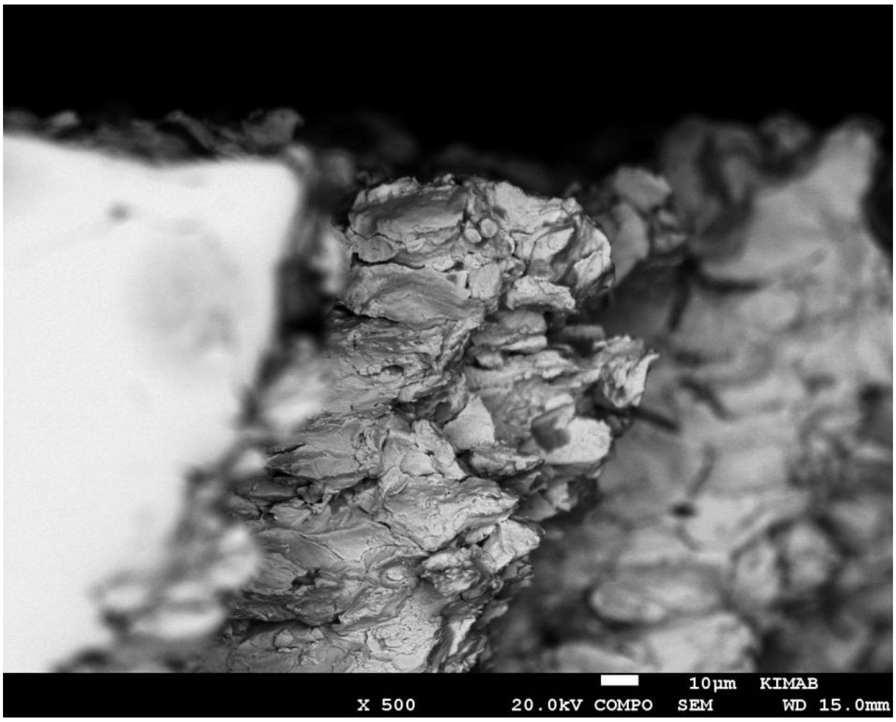

Figure 105. SEM-picture from the crack in the stainless steel, 500X.

An EDS- analyse in the region between nickel and stainless steel showed that there was no mixed zone.

Conclusions:

- The cause of the unsuccessful trial with soft cooling was due to an unprofessional processing of the cold spray by GfE.
- The process seems to have potential to be a future cost effective method but it needs a lot of process development for this special case.
- Further activities of process development with cold spray for soft cooled mould can soon be made by Swerea KIMAB thanks to the investment in cold spray equipment which will be installed in November 2010.

6. Results from experiments at Outokumpu Stainless, Avesta

The trial of heat no. 2339 in Avesta was made mostly with the aim to study the cold spray technique and there was no ambition to instrument a mould for further study of the impact of temperature distribution in the mould. The mould in Avesta is though equipped with a Mould-Expert system where important information is logged once per second. This includes two rows of thermocouples, heat flux from mould and mould friction. This information has been studied by Peter Andersson for the test heat and reference heats in conjunction with the test for similar steel grade and mould geometry.

In Figure 106 the tundish temperature for the experiment heat and two reference heats are shown.

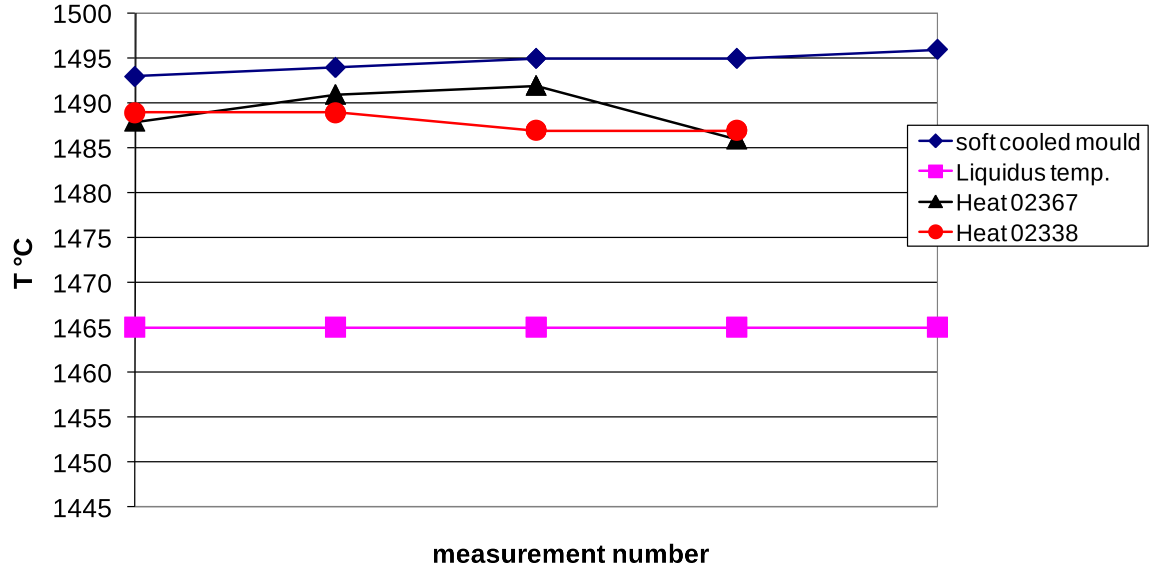

Figure 106. Tundish temperature for test- and reference heats.

The tundish temperature is somewhat higher for the experimental heat.

In Figure 107 the temperature is shown from the two thermocouples installed in the narrow side mould, 210 mm and 325 mm from the upper side of the mould.

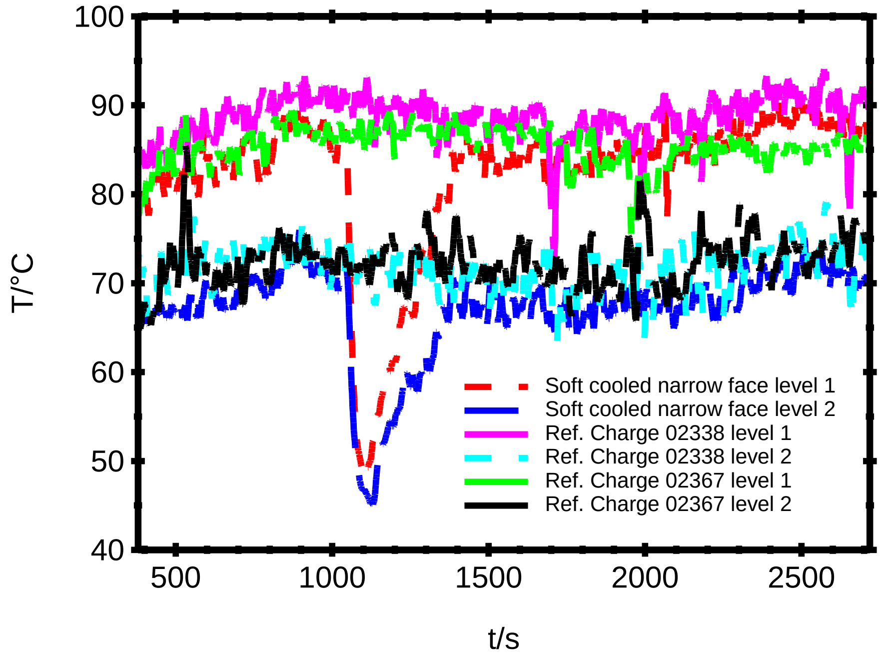

Figure 107. Temperatures from thermocouples in soft cooled mould and in a reference heat.

There is a clear temperature difference with a lower temperature for the soft cooled mould.

The results from the temperature measurements are shown in Table 19.

Table 19. Temperature differences between test with soft cooled mould and reference heat

Temp. difference high level	3.63 °C
Standard deviation-high level	2.92 °C
Temp. difference low level	2.90 °C
Standard deviation-low level	2.60 °C

Further remarks:

- No differences in mould friction which was not to be foreseen because the narrow side has little impact on the total friction.
- No difference in heat flux from the narrow side.

7. Feasibility study for implementation at SSAB EMEA in Luleå

In the original plan of the project an implementation of the soft cooling mould technique on a suitable steel plant was planned. Because the experiments were more complicated and time consuming than foreseen the project time and financing was not sufficient to fulfil this ambition within the project. To prepare for a future implementation with a short time of accomplishment a feasibility study was made instead.

The Swedish steel plants cast a great variety of steel grades on the same machine. Of that reason the introduction a soft cooled technique calls for a reconstruction of the continuous casting machine. It must be able to cast at different levels:

- A high level for casting of crack sensitive steel grades where full effect of the soft cooled mould is needed.
- A low level below the soft cooled zone for casting of steels where a strong cooling is needed.

To fulfil these needs the CC-machine need the following abilities:

- A deep mould with sufficient length to manage safe castings even when casting below the soft cooled region.
- Possibilities to move the tundish and SEN downwards the mould at least 100 mm.

Within the project group the implementation for soft cooling had been discussed for a long time and especially the conditions to realize it at the project member's steel plants. From these discussions it stood clear that an implementation for most steel plants is connected with a large investment for new extended moulds and reconstruction of the ladle support system. The only steel plant that had good chances to implement the soft cooling technique to acceptable costs was SSAB EMEA in Luleå. Christer Nilsson from the project team was therefore requested to make a feasibility study for an installation in Luleå.

The cost for implementation in Luleå is restricted to investments in new moulds and the cost for the welding (cold spray?) of the soft cooled layer of the following reasons:

- The mould is already sufficiently long with a depth of 900 mm where the castings normally is made at a level of 750-800 mm.

- The new system for steel level control (SERT) makes it easy to change the steel level in the mould.
- It is possible to vary the depth of the SEN at a maximum of 150 mm, where the minimum steel level for safe casting is 650 mm.

A soft cooled production for SSAB EMEA could therefore be done with the following technique:

- Installation of a soft cooled layer at the position of 700 to 820 mm from the bottom.
- Casting of peritectic, crack sensitive steel grades will be done on the 800 mm level where 100 mm of soft cooling is utilized.
- Casting of steel grades with a need of medium or strong cooling as, ferritic ULC-steels, is done at a level of 700 mm just below the soft cooled region.

8. Summary and conclusions

The technique with soft cooling in the upper part of the mould can reduce the heat flux of about 20 % provided a thickness of the thermal barrier to be about 8-9 mm.

- This thickness of the thermal barrier results in a surface temperature of about 850 °C which is on the safe side if a temperature resistance stainless steel or nickel is chosen for this purpose.
- The metallurgical effect with soft cooled mould is low if the casting is made with a highly crystallising mould powder, with an evolution of a thick slag rim, while this can reduce the heat flux with up to 50 % and block the effect of the soft cooling mould.
- A positive metallurgical effect is obvious if the casting is made with an amorphous, glassy mould powder with a low tendency of slag rim formation. This is proved by avoidance of "hook" formation during the initial solidification and lower oscillation mark depth and also wider secondary arm spacing (lower solidification rate).
- The technique with soft cooled moulds has a potential for casting of crack sensitive steel grades with much less variations in heat flux from the mould. This can be achieved by avoiding a strong crystallising mould slag, using an amorphous slag and let the soft cooling layer reduce the heat in a much more reliable way.
- The soft cooled layer can be produced with welding technique but this requires nickel as soft cooling material to avoid hot shortness, which is the case for welding with stainless steel due to high levels of copper in the weld.
- Cold spray could be an alternative way to prepare the moulds for soft cooling because it has a high coating efficiency.
- The experiment in Avesta, with a cold sprayed soft cooled layer which only lasted for one heat due to surface cracking, showed that there is a need for process development of the method to increase the strength of the soft cooled layer.

9. Potentials for energy savings by using the soft cooling technique.

At the time when the application for the project was written (2006) an estimation of the energy saving potentials for reduction of surface cracks were made for SSAB EMEA – Oxelösund, Sandvik Materials Technology and Outokumpu Stainless AB Avesta works. The energy consumption consisted of four items:

1. Reduced electrical consumption due to less use of grinding machines.
2. Increased yield due to less grinding losses.
3. Increased yield due to less scrapped heats.
4. Possibilities to convert ingot cast steels to continuous casting.

With this background the following energy consumptions were calculated:

- SSAB EMEA Oxelösund:	26 GWh/year
- Sandvik Materials Technology:	20 ”
- Outokumpu Stainless AB, Avesta	15 ”
- Total:	61 GWh/year

The potential savings by implementing the soft cooling technique in all three steel plants was estimated to be 50 %, that is: 30.5 GWh/year.

To be able to update this estimation the steel companies have been urged to make new estimations of the energy saving potential based on their current situation.

SSAB EMEA Oxelösund and SMT state that their situation is unchanged and that their energy potential is unchanged.

The input from Outokumpu Stainless is that they have the same estimation as from year 2006, but they want to add possible energy savings by increased casting speed enabled by the soft cooling mould technique according to the following calculation:

Energy reduction in steel furnace:
- Increased casting speed enables a decrease of casting temperature with 10 degrees.
- The tapping temperature from AOD furnace can be reduced with 10 degrees by the addition of 1000 kg more cooling scrap which reduces the melt demand with 1000 kg per heat.
- The melt energy for 1000 kg scrap is 450 kWh.
- The yearly production is 4500 heats, which reduces the energy consumption with:
  4500•450 = 2.0 GWh/year

Energy savings in the casting machine:
- Increased casting speed means lower electrical consumption for pumps, motors etc.
- 10 % increased casting speed means 20 kWh/heat in energy savings.
- 4500 heat per year means 4500•20 = 90 MWh/year.

Total energy saving by increased casting speed with 10 %
2.025.000 + 90.000 = 2.115.000 kWh/year = 2.1 GWh/year

The potential by introducing the soft cooling technique is still 50 % based on the results from the project which gives an updated energy saving of: (61+2)/2 = 31.5 GWh/year.

SSAB EMEA Luleå did not participate in the original project proposal. Thus their energy saving potential is not included in the estimations above. They have, however, participated in the project committee from the beginning. Their estimation is that 10 GWh per year can be saved in steel works in Luleå if surface defects of crack sensitive steel slabs can be lowered by 50%. Early detection of surface defects will avoid transportation by train to the rolling department as well as unnecessary rolling and further treatment. The energy saving of the latter are not included.

10. Suggestions for further activities

The work within the project had to be concentrated to gain competence regarding the effect of soft cooling in regards to heat flux and solidification. Further a big focus was put on how to achieve an industrial viable method to manufacture the soft cooled layer. The ultimate goal of the project, to reduce energy costs by production of crack sensitive steel grades with minimum risk of surface failures has not yet been tested in full scale. Therefore a proposal has been sent to Energimyndigheten (Swedish Energy Agency) with the title “Utveckling av stränggjutningskokill med mjukkylande egenskaper - Etapp 2. The goal with this proposal is the following:

- Tests with the loose broad side mould at SSAB EMEA in Luleå. The tests will be done with the concept soft cooled mould in combination with mould powder with low ability for crystallisation while casting crack sensitive peritectic steel grades. The focus of the project will be to study the metallurgical effect regarding surface quality.
- If the process trials turn out to be as positive as hoped a second phase of the project will be made which includes a full scale testing with all of the mould sections prepared with soft cooling.

11. Acknowledgements

All industrial partners, the chairman Tomas Sohlgren at SSAB EMEA Oxelösund, Karin Hansson Antonsson at SMT, Christer Nilsson at SSAB EMEA Luleå and Ravi Vishnu/Jesper Janis at Outokumpu Stainless are much thanked for their great interest and large efforts they have made during the project time especially when it comes to perform the difficult industrial trials at their steel plants. This great interest is also proved by the large number of project meetings during the project time, totally 27 project meetings have been held from 6/12 2006 to 4/10 2010 whereof 12 physical meetings and 15 telephone meetings.

Lars-Henrik Österholm at Jernkontoret is also much thanked for his encouraging attitude, always helping the project forward especially when the difficulties seemed overwhelming.

Finally, Energimyndigheten (Swedish Energy Agency) and especially Anita Larsson is much thanked for their financial support and great interest in the project.

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