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VALorisation and dissemination of RFCS projects results and experience in steel surface quality issues: on as-cast CRAcks formation

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Cover sheet of 88 subsequent pages

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1 Foreword

Continuous Casting (CC) of steel has been a major development of the steel industry during the last 50 years. CC has increased the competitiveness of the steel industry due to both, the higher productivity ratios of this route, and the lower production costs. As a consequence, the ratio of steel produced by the CC route has continuously increased along this period time. Additionally, another important factor of CC route is the reduction of the environmental footprint when compared to the ingot casting processes.

On the other hand, the major disadvantages regarding the ingot-casting route is the complex solidification processes and the frequent development of cracks in the inner and surface of the of the CC semis. Due to this cracking problem of the CC route, many European funded projects have been devoted to study the causes of the semis cracking, and to alleviate this problem. It could be thought that after so many years of research, the quality problems could already be solved, however, the updated situation is that although the quality has improved, the situation is still far from being solved. There are several reasons for this outcome, among others, the followings are relevant:

1. The complexity of steel grades which are produced by CC is increasing year by year: microalloyed steels grades; microalloyed steel grades with high sulphur contents to increase machinability; boron steel grades, high manganese steels.
2. The demands for higher productivity have raised the casting speeds of the CC machines along with associated cracking problems.
3. Related to previous mentioned two reasons, is that many of the defects are linked to in-mould solidification. The studies have shown that a good contact between the solid shell and the copper mould is of a paramount importance in order to avoid defects. At this aim, parabolic taper moulds have been designed. However, each steel grade and each casting speed would require an optimum taper, which is impossible from an industrial practice.
4. Customer requirements for better surface and internal product quality have increased along years.
5. The development of improved methods and tools to detect small defects in as cast semis and in rolled products.

All the above reasons have increased the interest of the steel producers in crack development during CC processes.

2 Structure of the report

The present deliverable D3.1 analyses all the collected European funded projects in order to evaluate the influence of the research on the improvement of continuous casting process.

This report is divided in sections according to the topics defined in D2.2 and, despite the different nature of each topic, the structure reflects in general the collection of information about the following main points:

1) Evolution of the state of the art in the last 15 years: influence of the research work in the validation or modification of the departure situation, reasons of success or failure of the projects.
2) Best practices or solutions: most useful and validated practices, technologies, last developments…
3) Future developments: most promising and useful emerging development lines, future trends.

The various aspects of CC technologies are divided following the same criteria adopted in D2.2. As a recall, five main topics have been detected:

1. Basic Knowledge
2. Modelling
3. Process Optimization
4. Mould powder
5. Process control & sensoring

Every topic was studied in deep by each partner, based on their experience and their involvement in the RFCS projects.

The present document is intended to be a critical analysis of the European continuous casting technology panorama. The analysis of the results allowed to VALCRA project to assess the most useful technologies and knowledge, including a careful look to recent progresses present in scientific literature, the reasons of failure and main critical issues related to the various topics.

All these aspects have been considered in the preparation of the present document; however, every topic has a different structure, due to the different approach that is followed in the European projects.

The document is prepared in order to provide a useful tool for dissemination activities and to track the final roadmap.

3 State of the art by topics

3.1 Basic Knowledge (SIDENOR)

The main objective of the present topic is to understand how chemistry, microstructure, solidification pattern and applied or induced stresses influence the occurrence of crack formation during the continuous casting of steel. The vast range of defects frequently observed on the final products can be related to one or more of the previous factors. Since the majority of European projects analysed the causes that led to the formation of one or more specific defects, it was decided to follow the same approach in the definition of the influence of research project on the understanding of crack occurrence in continuous casting. For that reason, the approach followed in the present section refers to a particular kind of crack and defines its origin and possible countermeasure.

Figure 3-1 shows a sketch with different kinds of cracks frequently observed in slabs and billet/blooms. A first division which can be made is:

- **Internal cracks.** The internal cracks can be split on the following:
    - **Segregation cracks**, also called ghost lines, inter-columnar cracks. They appear frequently filled with segregation of low solubility in iron elements as S, P, B…These cracks are produced by stresses in the solid/liquid interface during solidification. This is the case of the following kind of defects:
        - Off-corner cracks
        - Half-way cracks
        - Internal transversal cracks
    - **Solid stress cracking**. There are internal cracks which develop on the solid:
        - Central star cracks
        - Transformation longitudinal cracks
        - Corner cracks

- **Surface cracks:**
    - Intergranular cracks
    - Transversal cracking
    - Longitudinal cracks
    - Transformation longitudinal cracks

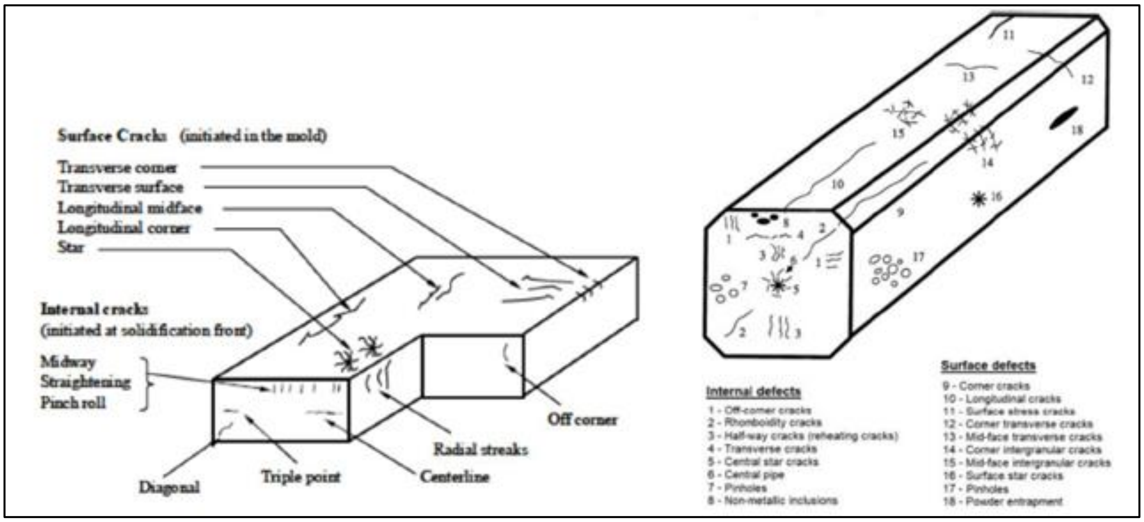


Figure 3-1: Different kinds of cracks, which can be observed in the CC semis. Left, slabs [10]. Right, billets/blooms [11]

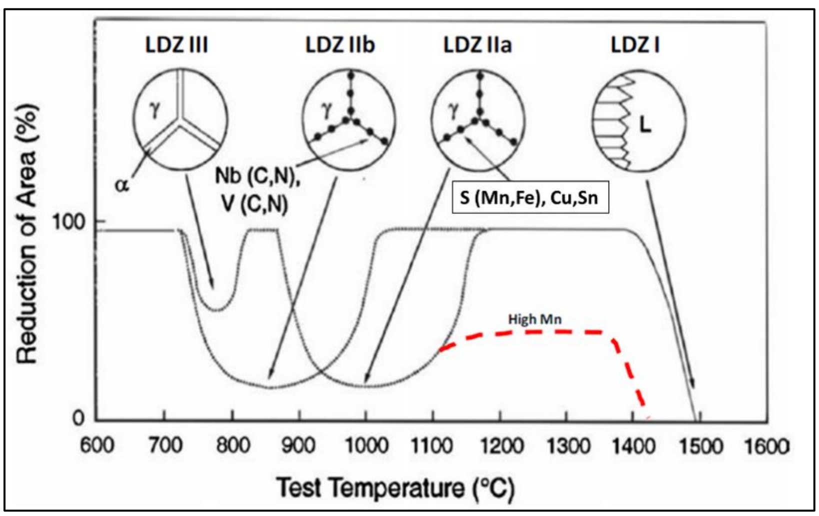


Figure 3-2: Low ductility zones and main mechanism responsible for it during solidification and cooling of micro alloyed steels grades [12]

Figure 3-2 shows the three different low ductility zones (LDZ) which the solidifying shell experiences during solidification and cooling in the CC process and the main chemical elements responsible for that low ductility [28].

Each of the above-mentioned cracks could be related to one of those low ductility zones.

The first low ductility zone (LDZ I) is related to the solidification temperature interval between the temperature the material starts to have some mechanical strength and the temperature when the microstructure is able to withstand some strain before breakage: this low ductility temperature interval is related to the temperature interval with low melting segregated inter-dendritic liquid.

In the second low ductility zone (LDZ IIa), the ductility trough is related to the precipitation of MnS at the austenite grain boundaries during cooling, together with the embrittlement produced by liquid Cu and Sn penetrating through the surface austenite grain boundaries. It extends between approximately 1000 and 1200 ºC. This LDZ IIa is sometimes overlapped with the ductility decrease produced by micro alloying precipitates LDZ IIb.

The LDZ III is related to intergranular ferrite precipitation at the beginning of austenite decomposition: ferrite begins to precipitate in the austenite grain boundaries (intergranular ferrite). As the ferrite is softer than the austenite, the strain during deformation concentrates in the ferrite with the corresponding ductility decrease. The ductility recovers when ferrite content is higher than 40%.

In addition, Figure 3-2 shows as a red dashed line: the low ductility zone which is obtained at high temperatures for high Mn steel grades as it was experimentally tested in recent PMAP project [EU-1.] for steel grades with a Mn content between 18 and 25%. The research on this high Mn steels grades is quite recent and a very limited application to CC of high Mn steels have been reported so far, due to the high problems when casting.

LDZ I plays an important role in the formation of segregation cracks: it is devoted to the influence of chemical elements in the extent of LDZ I and their influence on casting parameters.

The majority of the surface cracks in CC semis are related to LDZ II and LDZ III.

Finally, the origin of thermal/transformation cracks is related to LDZ II and III, and they are sometimes panel cracking (for ingots) or perlite transformation cracking. The cracks are mainly internal however, sometimes go up to the surface. The formation mechanism is different respect to the other cracks

For all these kinds of cracks, it follows a detailed description, considering the influence of chemical elements on the ductility reduction and the combined influence of this low ductility and casting conditions on their formation.

3.1.1 Segregation cracks

LDZ I is related to segregation of certain elements to the interdendritic liquid, producing a low melting temperature liquid between dendrites. Under these circumstances, any strain produced at the solidification front before the end of solidification will be able to tear the material leading to the formation of internal segregation cracks. Throughout the previous ECSC and recent RFCS programs there have been a number of projects aimed at the understanding the influence of chemistry on segregation cracking ([EU-1.] [EU-7.] . Over the years there have been many papers treating the same matter, among them the papers can be mentioned [13][18]. Following general comments can be done of this European projects and international literature. The early paper of Clyne et al. [13] treats the matter of microsegregation of low solubility elements in the interdendritic liquid, and the role played by carbon on the microsegregation. As carbon is the main element influencing primary solidification phase, δ-ferrite or austenite, carbon will have influence on the microsegregation of the other elements. The internal cracking susceptibility will depend on the extent of the temperature interval of the interdendritic liquid for high solid fractions. A Crack Susceptibility Coefficient (CSC) is defined linked to this temperature interval, the higher the temperature interval, the higher the crack susceptibility. In the [EU-5.] *(Study on brittleness of carbon steels during solidification)* report, experimental work is carried out producing deformation of ingots during solidification and studying the influence of the composition on critical strain for producing internal cracking. It is shown that sulphur is the main element influencing the extent of the interdendritic temperature interval.

Schmidtmann et al. in two early papers [14]- [15], described the results of many hot ductility tests on in-situ melting samples. They define the Zero Strength Temperature (ZST) which is the temperature when the material begins to be able to transmit any stress, this temperature takes place when the solid fraction is in the range 0.6-0.8. The Zero Ductility Temperature (ZDT) is also defined, , which is the temperature when the material is able to withstand some strain. The ZDT is found for a solid fraction of 0.99 or 1. The main conclusion of this work is that the formation of segregated cracks is related to the temperature difference between ZST – ZDT. The experimental work of Schmidtmann et al. shows that S and Mn/S ratio plays an important role on the extent of ZST-ZDT. Many papers have been published afterwards, which show the influence of Mn/S ratio on the formation of internal cracking. In addition to these papers, ICCRACK project [EU-7.] shows this influence of S and Mn/S ratio on internal cracking. This project and the paper [18] demonstrate that there is a (Mn/S) critical ratio for avoiding internal cracking, and this critical ratio is dependent on the S content and can be calculated by analytical expression [EU-7.] [EU-9.]

Another element which causes segregation issues is boron. This element is used as a microalloying element, and its use has increased during recent years as a cheap way of increasing steel hardenability. The segregation ratio of boron at the interdendritic liquid during solidification is almost the same than S and the influence of this element on segregation cracking has been studied in a recent PMAP project [EU-1.] and is continuing studied in the on-going project PMAPIA [EU-23.] . The PMAP project demonstrated that boron enhances the internal segregation cracking, and its influence is difficult to control. In the case of S, the addition of a Mn content higher than the critical value limits the S enrichment in the interdendritic liquid, avoiding the formation of low melting liquid, which ends solidification with the precipitation of FeS at around 1000 ºC. However, the B content of the interdendritic liquid increases during solidification up to precipitation of Fe_2B at around 1050 ºC. Therefore, the extent of the ZST-ZDT is very large, and also the internal cracking tendency. The PMAPIA [EU-23.] project is aiming how to solve this problem.

There are two major parameters affecting the presence of segregated cracking: a steel composition with a high susceptibility for cracking, this is a high ZST-ZDT, and the development of a stress in the solid/liquid interface. There have been many EU supported projects and published papers trying to know the magnitude of the stress producing segregation cracking and the causes by which those stresses may be produced during the CC.

The effect of casting process variables on development of stresses during casting has been studied in the following European projects [EU-2.] [EU-7.] [EU-9.] and [EU-15.] . The influence of billet mould friction force on the internal segregation cracking has been described in the ICCRACK project [EU-7.] . The MONITORING project [EU-3.] and EXTENSION MONITORING project [EU-15.] relate the formation of internal cracking to the increase of the billet/mould friction force. On-line friction measurement systems are developed on those two projects to control friction force and to minimize the internal cracking and the production of breakouts. ICCRACK project [EU-7.] also shows both, the influence of billet surface reheating at the transition between consecutive secondary cooling zones, and at the end of the secondary cooling zone with the development of internal cracking. This experimental work was developed for billets and for blooms and it was shown that reheating in the range of 100 – 120 ºC are able to produce internal cracking for sensitive steel grades.

The strains associated with strand bulging, roll misalignment and unbending are studied in different projects mainly for slabs CC [EU-3.] [EU-5.] [EU-7.] [EU-10.] [EU-11.] [EU-12.] [EU-13.] [EU-14.] . The ICCRACK project [EU-7.] , which is the most recent one, collets many of the results of previous projects. In this research, it is shown that a measured roll misalignment of 2 mm can produce internal cracking in slabs. Furthermore, the load on the frame during casting can misalign the machine. It is also shown that the CC frame heating during casting can also produce some machine misalignment.

The investigation of the effect of mechanical soft reduction is studied on [EU-16.] and there is a recent paper published in 2019 [20], which collects many of the researches carried out during recent years. Mechanical Soft Reduction (MSR) is applied at the end of the liquid pool to compensate the volume decrease during solidification, and to avoid the flow of segregated liquid towards the semis centre. The reduction in semis size produces stresses in the solid shell and in the solidifying semis centre. Many of the research carried out in this matter is made by means of models to optimize the position of the strand where the MSR should be applied, and to calculate the strains which are developed in the semis during MSR.

It is acknowledged that mould electromagnetic stirrer (EMS) produces a modification of the inner semis microstructure with high improvement of quality. Due to this fact, EMSs have been implemented in many CC machines. However, the Magnetohydro project [EU-8.] and ICCRACK projects [EU-7.] showed that in mould EMS can produce a modification of the solidification in the corner area which can enhance the presence of off-corner segregation cracks in the corner side against the EMS induced flow.

3.1.2 Surface cracking

Surface cracks are formed in the CC semis due to the combination of stresses developed at the semis surface and the temperature of the semis surface being one corresponding to a low ductility zone. The low ductility zones are those corresponding to LDZ IIa, LDZ IIb and LDZ III. Each of them corresponds to different temperature ranges and to a different metallurgical mechanism. The one having more importance is the one related to LDZ IIb, which is produced by the precipitation of microalloyed particles and the LDZ III which is produced by the precipitation of intergranular ferrite. The importance of these

LDZs is that they correspond to the temperatures of the billet surface during straightening, and the problem of surface cracking on this LDZ has soared during recent years due to the increase of microalloyed steels grades.

Micro alloyed steel grades are steels where small amounts of Al, Ti, N, V, B, Nb are deliberately added to improve the mechanical properties of the steel. Their amount produced by European melting shops dedicated to engineering steel production has increased during the last decade, reaching in some cases almost 95% of the total production. Furthermore, S is added to many of microalloyed steel grades to improve machinability. Almost half of the micro-alloyed steel grades with V, Nb and B produced at Sidenor steel mill, also contain sulphur to increase machinability. As it is observed in the Figure 3-2, the high S content of microalloyed steel grades may produce the precipitation of MnS on grain boundaries during cooling.

Some EU supported projects have studied the surface cracking during CC. In the year 1996, the CRACK PREVENTION project [EU-17.] established the influence of Al*N compositional parameter on the surface cracking of semis on two industrial partners, British Steel and Dillinger. Values of Al*N higher than 2*10^-4 (%*%) increase the frequency of surface cracking in cast semis. Furthermore, in the project they were able to relate some of the cracks to the straightening operation, due to the fact that the occurrence of cracks was higher in the loose semis side than in the fixed one. The project also called the attention on the importance of machine alignment on surface quality.

The HIGH TEMPERATURE SURFACE CRACK project [EU-18.] was finished in the year 2003. It showed that intergranular surface cracks are related to large austenite grain size (AGS) during casting. Large AGS are formed at the oscillation marks valleys due to reheating by loss of contact with the mould, and the combination of large AGS and intergranular ferrite during straightening operation produce intergranular cracking (LDZ III issue). The project tested different methods to get rid of this problem, as to produce temperature cycling of the semis surface or to practice highly intensive secondary cooling in order to unbend after complete surface austenite decomposition. However, they found that temperature cycling produced surface cracking.

The NEW SECONDARY COOLING PATTERNS project [EU-19.] was also finished in the year 2003. The project explores similar technologies than the HIGH TEMPERATURE SURFACE CRACK project [EU-18.] in order to reduce billet surface cracking. They found the strand surface temperature cycling improves ductility and that this practice is important to use mainly for hot charging of semis to the rolling mill. The differences on results of the high temperature cycling method with the HIGH TEMPERATURE SURFACE CRACK project could be due to difference in the steel composition tested between both projects.

Additionally, the influence of microalloyed content on surface and internal cracking has been studied on four consecutive projects carried out from 2001 to 2020. There has been some continuity among these projects as some of the partners are common in all of them, as is the case of Tata steel, Sidenor, Swerin and RWTH Aachen. Others have changed as Thyssen Krupp Stahl, VAS Donawitz, Arcelor Mital, CEIT, VAI Linz. These projects are the following: NITRIDES [EU-20.] , PRECIPITATION [EU-21.] , PMAP [EU-1.] and the on- going project PMAPIA [EU-23.] . Main knowledge collected thanks to those projects is the following.

On one hand, The NITRIDES project [EU-20.] was mainly devoted to characterising the sequence of precipitation during cooling, depending on the steel composition. Different software was used by the partners, and the results were compared with precipitates observed in cast semis. The influence of Ti and TIN precipitates on surface quality was studied.

The PRECIPITATION project [EU-21.] explores the influence of the hard/soft cooling practices. Laboratory experiments reveal that the possibility of using hard secondary cooling below the Ar3 temperature can be further exploited on industrial scale for better high temperature ductility and to reduce internal segregation cracking on slabs. Good surface quality is obtained with soft cooling for billets. The influence of in-mould solidification on precipitates formed showed that the mould powders performance is the main factor influencing the solid shell cooling rate. It is observed that the combination of powder basicity and viscosity are both important factors affecting cooling rate. The influence of tertiary cooling conditions and steel composition on the development of transformation cracking is studied. This kind of cracking is getting more important in the update CC machines due to the increase in the casting speed and the need to take out of the tertiary cooling the semis at higher temperatures, which could favour the formation of transformation cracks.

The PMAP project [EU-1.] finished in 2016. It studied the role played by boron on internal and surface cracking of billets. It also made a further study of factors influencing the cracking in the tertiary cooling. The influence of S and Mn is studied. A model is developed to calculate the S remaining in solution at the austenite after complete solidification, considering the interdendritic MnS precipitation. The quantity of S in solid solution able to produce grain boundary loss of cohesion during cooling has been characterized. This allows to calculate the S and Mn content of the steel in order to avoid the LDZ IIa related to MnS grain boundary precipitation. Eleven papers have been published by the partners of this project [21][31]

The on-going PMAPIA [EU-23.] project begun in 2018 and it will finish in 2021. The project is further studying the means for controlling interdendritic segregation of boron, which causes internal segregation cracks in billets and its role on cracks in the tertiary cooling. It is also attempting to clarify which is the major cause of intergranular surface cracks: the stresses developed at the secondary cooling or the stresses at the unbending machine. The project is also studying the influence of MnS secondary precipitation on the cracking during CC or in the rolling of as cast semis. The CC of high Mn steels is also studied.

The KINPCC project [EU-22.] has finished in the year 2014. It is mainly devoted to the characterization of the kinetic precipitation of microalloyed particles. At this aim, techniques to characterize precipitation are used, as it is the case of dissolution technique and TEM. Some of the results were described in the 2017 paper [32]. The study shows that thermodynamic precipitation models are not representative of precipitation, and a kinetic precipitation model is developed and compared with as cast precipitation results. VAI Linz, one of the partners of this project, merged to the ongoing PMAPIA project, adding to this project the experience developed on the KINPCC project.

3.1.3 Thermal/transformation cracking

This third section is devoted to the study of thermal/transformation cracking. This kind of cracks are mainly internal however, sometimes go up to the surface, producing the so-called panel cracks. The origin of these cracking is related LDZ II and III, and the cause is the stresses originated during austenite decomposition, due to the expansion associated to it. The magnitude of the stresses is higher when a massive transformation is produced like in perlitic steels, where the transformation is produced for a high quantity of material in a low temperature interval. The temperature where this transformation is happening occurs at the tertiary cooling. In order to avoid this cracking a slow cooling is required in order to avoid high temperature gradients inside the semis. In the case of slabs, special slow cooling is achieved in cooling box for sensitive steel grades. Bloom semis also requires methods for slow cooling. In the case of billets, the increase in casting speed in update CC machines has increased the thermal/transformation cracking, because sometimes the billets reach the end of tertiary cooling before austenite transformation is completed. This being a cause for cracking in sensitive steel grades.

The projects PMAP [EU-1.] and the ongoing project PMAPIA [EU-23.] are tackling with this problem. The main conclusions are related with the relation of this cracking with composition. The involved chemical elements are C, Cr and Mn, combined with microalloyed elements that precipitate during austenite transformation. The most dangerous precipitates are: AlN and BN.

3.1.4 Discussion and last development

There are many papers devoted to characterising the low ductility trough. Much of them investigated the influence of microalloyed elements on the LDZ IIb and LDZ III temperature extend. B. Mintz, from the City University of London, has published a lot of papers in this matter. Among them, [33], [34] and [35] describe the more important results. In 2009, Schwerdtfeger et al. [36] published a paper combining the knowledge developed on hot ductility trough temperature interval with the modelling of temperature and strain along the CC strand, with the aim of forecast the surface cracking of semis. More recently, in 2019, a paper is published [37] about the prediction of hot ductility of steels from elemental composition and thermal history by deep neural networks. The paper corrects some hot ductility test measurements; however, the application is only valid for the steel grades considered in the neural network adjustment.

The paper of Maehara et al. in 1990 [38] about the surface cracking mechanism of continuously cast low carbon low alloy steel slabs describes the importance of austenite grain size in the hot ductility trough LDZ IIb and LDZ III. It also applies the results to the surface cracking of billets and the importance of high temperature reheating in the austenite grain size (AGS). It has been mentioned how some European projects investigate further this parameter, and the studies which have been done to refine the AGS by means of surface temperature cycling in order to regenerate the austenite grain. Contradictory results have been obtained about the effects of this temperature cycling, as it has been reported before. Liu et al in a recent paper [39] show that for the grain refinement in the temperature cycling is important to know how the previous grain boundary remain after re-austenisation, depending this situation on the cooling rate during austenite decomposition. Fedosov et al. in a 2018 paper [40], also shows that transversal cracking depends on AGS (austenite grain size) and composition. The AGS depends on the end temperature of the peritectic transformation. This temperature can be adjusted with composition. Perhaps, these two papers could explain the scattering of results on previous research when comparing results when doing temperature cycling during casting. The way the temperature cycling is done, and the steel composition are both important parameters when judging the results.

Jansto published a paper in 2017 [40] which raised a doubt on the direct application to CC of the hot ductility tests. He proposes the use of the strain energy criteria, and to calculate this parameter along the CC strand. Maximum strain energy for cracking could be deduced from hot ductility tests, as the strain for Ultimate Tensile Strength (UTS). This paper and other similar papers show that the results obtained on hot ductility tests can give some information on the susceptibility of a steel grade to surface cracks when casting but are difficult to have a direct application. Much work is still needed in order to obtain a better prediction of surface quality.

3.2 Modelling (SWERIM)

Internal and external defects are recurrent problems during Continuous Casting (CC) of steel due to the introduction of new grades that are often difficult to cast, as well as the everlasting pursuit for higher quality and improved yield. Numerical modelling was introduced as an alternative to study Continuous Casting defects in a more cost-efficient way than using traditional trial-error tests in the plant (Figure 3-3). Starting in the late 70's and 80's with the advent of personal computers, the first generation of models managed to predict the overall behaviour of the caster based on empirical data and finite differences [86]-[88]. Subsequently, models in the 90's added Computational Fluid Dynamics (CFD) and solidification to casting simulations[89] [91]. Faster computers and improved codes allowed huge progress regarding multi-phase applications (e.g. bubbles and inclusions) combined with calculations of flow and solidification in the past decade [92] [95].

Currently, a wide variety of commercial and in-house codes are available for CC modelling such as PROCAST, COMSOL, TEMPSIMU, CON1D/2D, etc. [96]-[98]. Moreover, a recent trend is the development of thermo-mechanical models coupled to flow dynamics for solving the combined problem of flow, solidification and stress-strain during casting [99] [99]. Of all these, PHYSICA and THERCAST are two of the most promising approaches; which allow: a) 3D unstructured – mesh, multi-physics model using a combination of volume and finite element techniques (PHYSICA)[101] and b) a fully-coupled, thermo-metallurgical-mechanical, finite-element analysis coupled to a Navier-Stokes solver to calculate the stress-strain during solidification (THERCAST) [102]. Finally, significant efforts have been made by Beckerman *et al.*,[103] Gandin *et al.[104]* , Senk *et al.[105]* and others to bring microstructural modelling to usable scales for industrial application in CC.

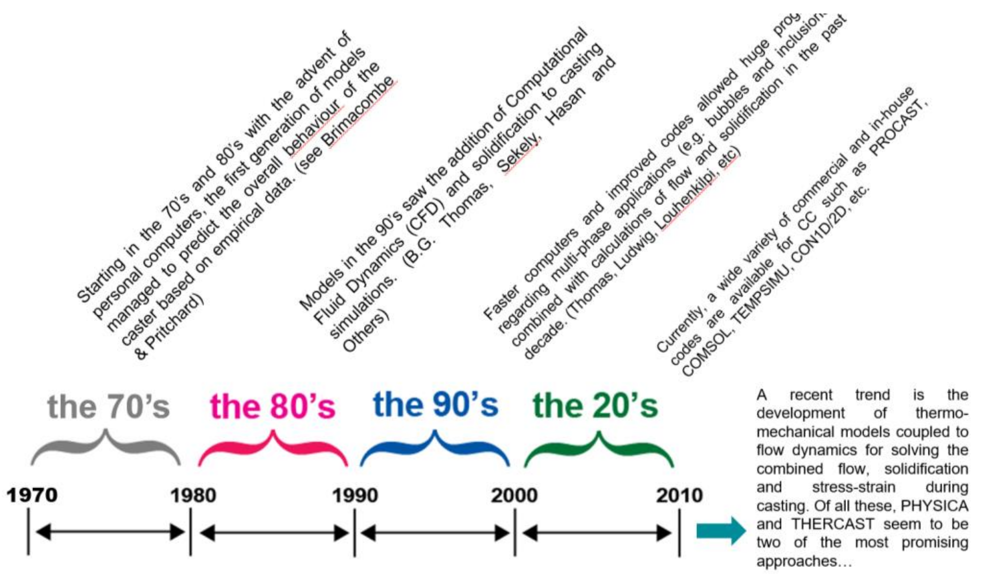


Figure 3-3: CC modelling timeline

3.2.1 Modelling of defects and cracking in CC

Despite all the advances described previously, the actual simulation of cracking has remained elusive from modelling efforts. This is partly due to the Multiphysics nature of the problem (e.g. dependent on heat transfer, solidification and stress-strain) as well as the high temperatures at which the process occurs (which limit possible measurements and data acquisition). Furthermore, there is a clear differentiation on the modelling approach depending on the final focus of the analysis. For instance, process models are typically based on macro-scale FEM methods that aim at predicting the total strain and stress coming from the elastic, thermal and plastic strains by means of thermo-mechanical models [99],[102],[106]-[112] (figure 3-4).

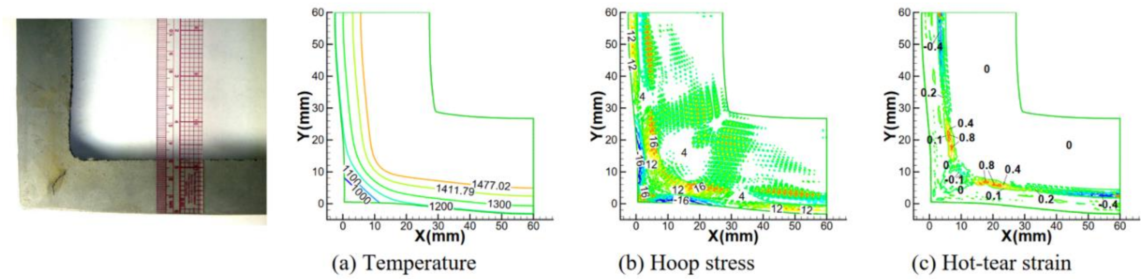


Figure 3-4: Corner cracking in CC (extreme left) and thermo-mechanical modelling results by Bellet & Thomas [114]

In contrast, focus on the microstructure typically implies micro-models ranging from Phase-Field and all the way to Meso-scales with Cellular-Automaton Finite Element (CAFE methods) [114]-[120]. However, these models focus strongly on the solidification and microstructure evolution (often coupled to CALPHAD methods) to describe the cracking mechanisms in steels. Clyne, Wolf and Kurz are pioneers of such treatment which employs partition coefficients and diffusivity data from the literature to operate back-diffusion models coupled to cracking susceptibility criteria which could predict the influence of carbon content in cracking [121]. Ultimately, cracking behaviour during CC is strongly dependent on both the macro-scale thermo-mechanical behaviour of the strand and the micro-scale phenomena related to microstructure formation during solidification as well as the segregation behaviour of each particular steel. Recently, Bellet and Gandin have presented models that attempt to breach this gap by coupling the CAFE approach with an Arbitrary Lagrangian–Eulerian (ALE) formulation [122] or by means of envelope models to address the mesoscopic modelling of microstructure coupled to viscoplastic models for solidification and fluid flow in the caster, which are to date the state-of-art on modelling of defects in continuous casting [123].

3.2.2 Numerical Modelling of CC defects and cracking in European projects

Regarding the state-of-art in numerical modelling within RFCS projects; it is well recognized that most casting defects occur during the first stages of solidification in the mould. Thus, a number of research activities have been focused on initial solidification, shell formation and oscillation mark generation. This include the projects (MASTERBILLET) [EU-24.] (CASTDESMON) [EU-25.] , (FLOWVIS) [EU-26.] ,

(PRECIPITATION) [EU-27.] , (MAGNETOHYDRO) [EU-29.] , (DEFFREE – 2011), (LUBRIMOULD) [EU-30.] and (FOMTM) [EU-31.] . Modelling the evolution of defects is critical to determine mechanisms responsible for their formation. Recently, ongoing and completed RFCS projects CASTDESMON (where modelling and monitoring tools are employed to improve process control), LUBRIMOULD (which aims to improve mould powder selection) and DEFREE (through a modelling and statistical approach) represent the state-of-art European efforts to optimise the casting process and predict defects. MEFOS/SWERIM has recently developed an advanced CC numerical model able to predict the differences in lubrication, solidification and surface quality when casting different steel grades and casting powder combinations in DIRECT-DEFECT TOOLBOX [EU-77.] , NNEWFLUX[EU-80.] and SUPPORT-CAST [EU-82.] .

PROJECT EUR 19360 [EU-33.] is focused on numerical and physical modelling, as well as plant trials to determine mould conditions that improve slab surface and subsurface quality. Several modelling tasks were carried out successfully including modelling of the slag-metal interface (e.g. standing wave), slag layer modelling and nozzle design effects in 3D(e.g. standing wave), slag layer modelling and nozzle design effects in 3D [EU-32.] . However, coupling of these models with heat transfer was not possible. The physical modelling was carried out successfully on liquid metal with low melting point (ZnBr2) and water with different media to simulate slag (e.g. silicon oil, paraffin, etc.). The modelling work was able to successfully propose different mechanisms for slag carry-over and entrapment. These are based on vortex formation and shear rate at the interface due to flow coming from the jet and upper roll. Plant trials were carried out successfully at a slab caster in Raahe, Finland. Several modifications to nozzle design were proposed and tested based on the numerical modelling work to optimize standing wave (which was found as high as 37 mm at 1.75 m/min). Samples were taken from 1800 x 150 mm slabs to perform inclusion analysis finding mostly alumina and manganese sulphides. Slag entrapments were not detected in this analysis. Useful theoretical background and strategies for analysis of the critical velocity were presented. These are still in use today.

Modelling of primary cooling and plant trials were carried out in the frame of [EU-34.] . In this case, the objective was to determine how the mould taper in combination with shrinkage, operational parameters and other conditions (wear and distortion) affect the as-cast product quality of carbon and stainless steels. A full strand inter-roll bulging model was successfully developed. Calculations showed that improved taper profiles can reduce the gap between mould and shell to avoid compression and distortion (e.g. rhombicity). Laser measurements to characterize the as-cast profile below the mould were unsuccessful due to hostile environment. The models developed, lead to a deepening of various parameters that have a role in crack occurrence on the final product: mould level setpoints, interaction between the square shaped solid shells formed at the meniscus with a thermally distorted mould, changing mould level, frequency mould level oscillations were totally studied and tested in plant with positive results. . Recommendations for Improved mould level control, oscillation praxis, and optimised taper were given.

Correlations between increased surface crack defects and increased mould heat flux have been successfully analysed thanks to physical model for water flow in mould channels and FEM model to compute the resulting heat flux in the copper plates in [EU-36.] (*Optimisation of the straightening* *process in continuous casting*). The Fibre optic temperature measurements (FOTS) system was successfully implemented at Salzgitter slab caster providing a higher resolution in space and time for temperature measurements than thermocouples.

A model for the description of solidification of the steel inside the mould was one of the outputs of [EU-37.] (*INNOSOLID*). New mould geometries for better control of the dendritic structure of the initial frozen shell in the continuous casting of billets have been developed. The new moulds include an increased radius at the corners and face bulging (i.e. in-built parabolic taper. The 2D model included the effects of thermal field from the liquid steel and the influence of slag infiltration by means of a 1D model. Results of the simulations revealed that the risk of off-corner cracks is lower in the case of billets with large radii and concave faces. Simulations were carried out to identify the ideal taper conditions. Conclusions of the trials were that the new mould geometries improve quality of the rolled product with a decrease in scrapping of c.a. 30 %. Increased radius showed a clear beneficial effect, while bulging was ineffective. Despite the improvements, significant operational investments would be required to adapt production facilities to the proposed geometries. The models could be applicable for testing other mould designs.

The use of numerical modelling to study the secondary cooling zone was adopted inside two other RFCS projects [EU-33.] -[EU-35.] . The first one [EU-33.] (*Control of liquid slag carry-away and entrapment in the CC mould for a better surface and subsurface quality*) developed new cooling strategies based on numerical modelling of secondary cooling, laboratory studies of hot ductility and evaluation of as–cast microstructure. One of the partners of the project experienced that the influence of the casting parameters to the crack susceptibility of peritectic and microalloyed steel grades was successfully described and a numerical model for new cooling strategies was successfully developed to calculate the possible use of a quenching box.

In the second one [EU-35.] (*SOLIMOULD*) a 3D numerical models in FEM to simulate bending and multi-beam model were developed. All these models were used successfully to predict the evolution of stress-strain during the straightening process. The applicability of model predictions was assessed and validated in plant trials in 2 slab casters. Both models and trials confirm bulging deflections on the order of 0.3 mm. Although roll forces were accurately predicted by the models, surface speed could not be captured precisely in simulations. Trials also confirmed that the trapezoidal shape is caused by the unbending regardless of the unbending type (single point or multi roll). The dynamic Modelling provided the most comprehensive analysis of bending/unbending in slab casting at that point of time.

3.2.1 Assessment of European Projects

As described above, most of the European projects have an acceptable degree of success with direct implementation during the project and after the project in several cases. This points to a strong sense of industrial application of the models/results. However, the traceability of follow up projects is more limited as well as a proper assessment of the economic benefits after application of the models developed. Thus, it is difficult to assess if the projects did not lead to economic benefit or if this benefit was not registered by the industrial partners due to confidentiality or possibly due to later assessment. This points to shortcomings on the evaluation of the impact of the measured/projects despite the strong industrial value demonstrated during their execution. This could be better addressed in the forthcoming Horizon 2020 and RFCS program.

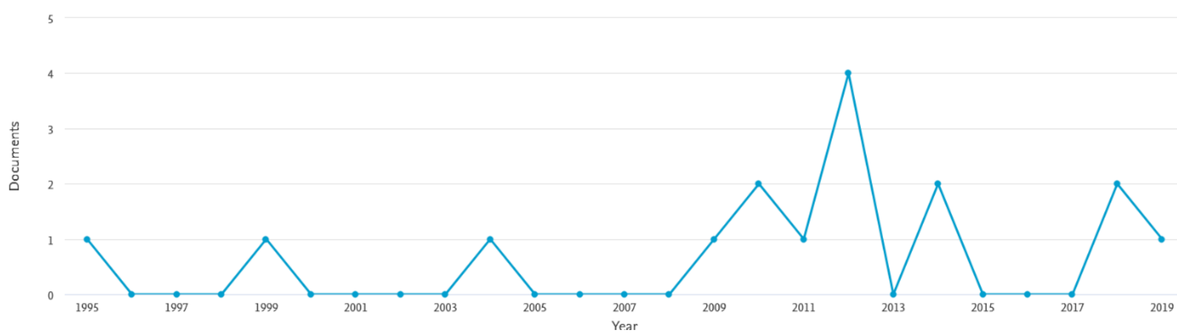


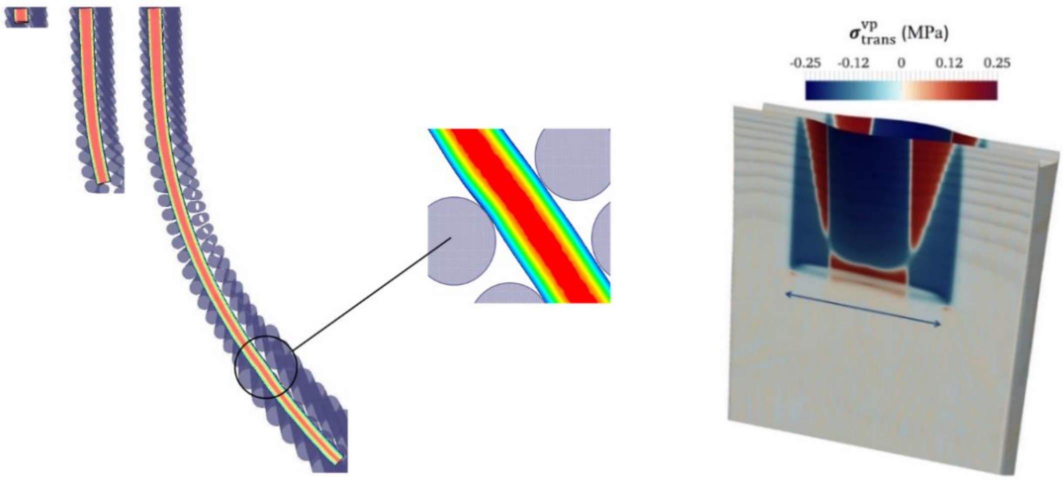
Figure 3-5: Publications related to Micro-modelling for cracking in CC in the past 25 years

3.2.2 Latest modelling developments

Recently, Bellet and Gandin have presented models that attempt to breach the gap by micro- and macro-models by coupling the CAFE approach with an Arbitrary Lagrangian–Eulerian (ALE) formulation [122] or by means of envelope models to address the mesoscopic modelling of microstructure coupled to viscoplastic models for solidification and fluid flow in the caster, which are to date the state-of-art on modelling of defects in continuous casting.

The classification effort in section 3.2.2 facilitates an analysis of the state of art and the leading groups in the world performing such investigations. Starting with the Thermo-mechanical approach, it is clear that B.G. Thomas' group at University of Illinois/Colorado School of Mines is the most active group closely followed by Prof. M. Zhu, in North-eastern University and Prof. D. Chen at Chongqing University, both in China. However, the contribution of all Chinese Universities and Institutes to the research field achieves more than 50 publications in the last 15 years which is at least 5 times the volume produced by the USA in second place and 10 times the output of Japan in third place. The majority of these publications focus on application of FEM methods in combination with CALPHAD methods to determine the effect of phase evolution during cooling on stress and deformation during solidification [118],[124]-[127].

Complex 3D thermo-mechanical models have allowed the prediction of stress and strain for a variety of cast formats and is as of today the favoured research approach to address cracking issues in casting, especially for simulation of solidification in the mould where most of the initial cast defects are generated (Figure 3-6)



a) b)

Figure 3-6: a) Snapshot of results for coupled flow and stress model by Costes et al.[128] and b) viscoplastic stress tensor in thin-slab casting by Ludwig et al. [129]

This is reflected by the significant number of publications with this approach that has exploded in the past 10 years (Figure 3-7).

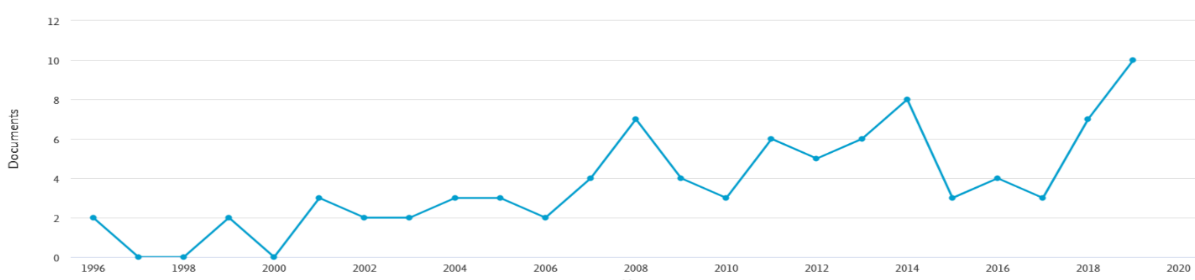


Figure 3-7:Publications on thermo-mechanical modelling for cracking in CC in last 25 years

In contrast, most steelmakers have internal mesoscopic models coupled to heat transfer and phase evolution. These simplified models (often 2D) are more widespread in the industry due to its fast response time and easy-to-use interfaces for process operators (e.g. CON1D [98] and TEMPSIMU [95]). For instance, extensive work has been carried out by Miettinen and Louhenkilpi with IDS/TEMPSIMU (figure 3-8) regarding modelling of segregation and its effects on cracking during solidification as a bulk by integrating a macroscopic model (TEMPSIMU3D+IDS) with a stochastic mesoscopic solidification structure model to describe phase evolution during casting with more than 10 publications in the past 15 years; [95], [130]-[135]. These are to date the state-of-art tools used by process engineers in the steel plants.

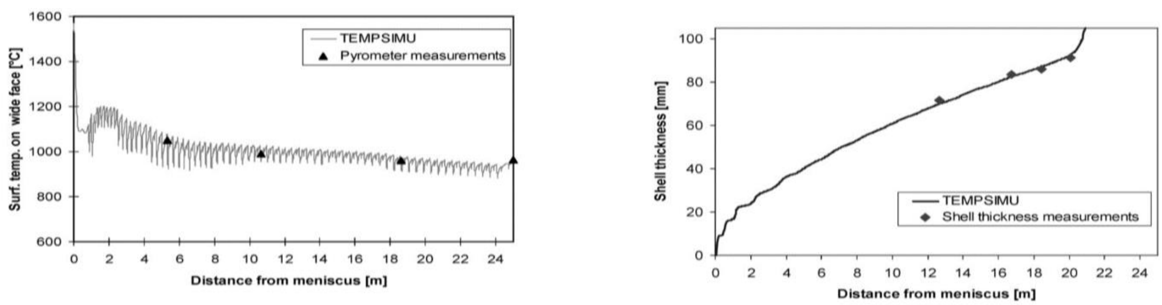


Figure 3-8:Temperature and shell thickness profiles predicted by TEMPSIMU compared to measurements [135]

At the other end of the scale, phase field models (figure 3-9) and Cellular automaton are used to predict the microstructure evolution of new generation steels. These are powerful tools to predict complex phase evolutions (e.g. twining, peritectics, retained austenite, etc) formation of precipitates and possibly predicting mechanical properties. For instance, the ACCESS team at the University of Aachen in Germany is the most prolific in terms of Phase Field calculations for steels with >20 publications in the period [105], [136]-[140] amongst others [141]-[143].

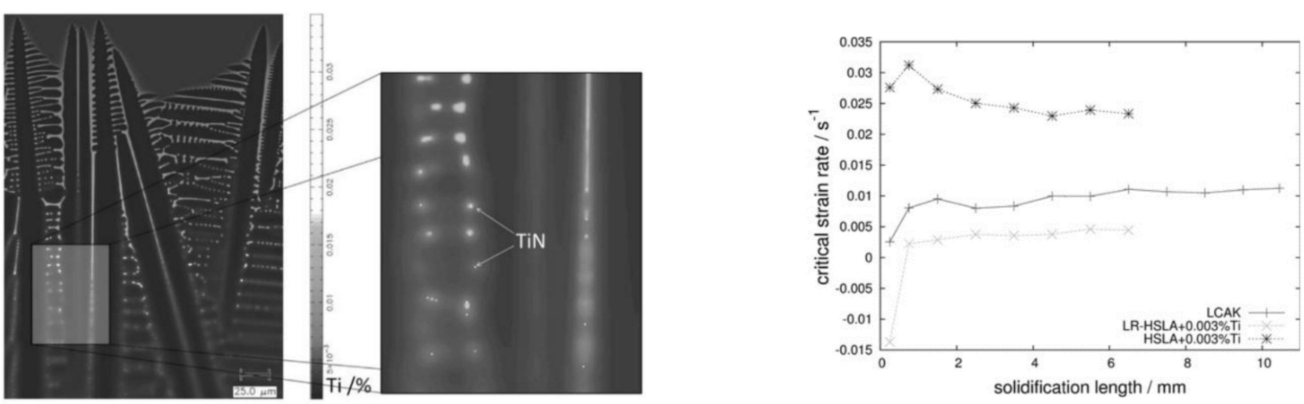


Figure 3-9: Predicted concentration of elements (Ti in HSLA) predicted by Phase-field approach and expected critical strain according to the Rappaz–Drezet–Gremaud (RDG) hot cracking criterion[144].

3.3 Process Optimization (CSM)

The definition of process optimization of continuous casting can be summarized as follows: definition of strategies such as tailoring operating practices and actions aimed to reduce the occurrence of surface defects in the final product, without detrimental impacts on productivity and safety conditions.

As consequence, parameter optimization covers the overall continuous casting process since many different parameters can be modified and adjusted in order to achieve an improvement in terms of product quality.

Moreover, the wide range of steel grades (carbon steel, stainless steel, microalloyed etc.) as well as the product final shapes (billet, bloom, slab, thin slab etc.) imply different approaches to improve steel quality. Finally, there are differences also in terms of plant layout that call for different strategies to be adopted.

Because of the variety of all these factors, it is not appropriate to list the process settings selected in the various RFCS projects; in the frame of offering a useful tool to produce and organize the dissemination events, the present document focuses attention on the relationship among the various continuous casting parameters that come out from the analysis of RFCS projects and recent scientific papers: new concepts of casting variables and their influence on the quality of the final product will be also described, as well as and the possible corrective actions that have been implemented.

As said above, the optimization of continuous casting covers almost all the aspects of the process; however, as reported in D2.2. the main topic was divided into four sub-topics:

- <u>Layout design</u>: modifications to the caster design to improve cracking performance
- <u>Operating conditions</u>: definition of operating windows which reduce potential for cracking. Definition of rules for downgrading due to potential crack generation
- <u>Injection techniques</u>: identification of specific techniques for inoculant addition to liquid steel to modify solidification
- <u>Improved steel compositions</u>: definition of steel chemical compositions for improving castability, to reduce defect occurrence

The sub-topics refer to the most relevant features that affect the quality of final products.

Among the 34 RFCS projects, 14 are characterized by studies concerning one or more of the process optimization sub-topics. In the frame of optimization of continuous casting process, the 14 projects are characterized by a common scientific and technical approach:

1. Analysis of current defect occurrence and analysis of casting conditions
2. Definition of numerical and/or physical models, based on customary or innovative modelling and monitoring systems
3. Simulation campaigns to study the effect of a range of process parameters (cooling system, mould taper, chemical composition, etc.), in order to reduce the presence of surface defects

4. Experimental campaign to test the feasibility proposed solutions, to bring appropriate corrective actions and to check any improvements on surface quality.

The present document describes the influence of research work of the last 15 years, as well as best useful and validated technologies, in the different subtopics, discriminating (when appropriate) between long and flat product and steel grade.

3.3.1 Sub-topic 3.1: Layout design

- Slab

The most relevant progresses in that area regard the understanding of tundish position and SEN wear, the adoption of different cooling system in the copper mould and taper design.
[EU-47.] (*DIRECT DEFECT TOOLBOX-DDT)* In order to minimize the wear of SEN the tundish is moved up and down. A parametric study with CFD model based on analysis of starting condition was performed: the simulation showed that when the tundish is in top position the risk is to have transversal cracks; when it is in bottom position, it is possible to have longitudinal cracks. New operative practice in term of SEN immersion depth have been studied using the digital tool. In that way the wear of SEN did not drastically increase, it was observed a reduction of surface defects. The improvement was more evident for transversal cracks than longitudinal.
According to [EU-47.] application of a magnetic field close to the meniscus results in a reduction of turbulent flow and turbulent heat transfer; CFD studies showed that hook formation and premature solidification can be corrected by switching off the FC-II (Electromagnetic flow control).
During the project INNOSOLID [EU-49.] mould copper plates have been changed: the aim was to assess if the modification of the cooling channel configuration in the mould copper using copper plates structured with grooves, could be beneficial in term of surface cracks (it influences the heat removal in the mould corners and at meniscus level). Seven geometry modifications were developed with the aim to reduce the heat removal in the mould corners and in the meniscus. However, no significant improvements respect to standard production have been detected, only marginal quality differences could be shown.
Changes in taper during casting can be correlated with both the mould end plate and broad plate temperatures [EU-40.] (*CASTDESMON*). In slab casting, the end plate distortion largely influences the taper along the whole mould length, (increasing it in the upper part of the mould, reducing it in the lower part). Improving the end plate performance was related to the reduction of off-corner depressions and cracks.

- Billet

Many works are related to the casting of the billets: investigations have been performed in limiting premature solidification, out of specification of billet profile, and general alternative mould geometry.
Non-uniformity of heat flux between steel and mould is one of the principal sources of defects.

An important parameter that influences many aspects of billet casting and their quality is the mould taper. The billet profile is influenced by carbon equivalent content due to shrinkage extent. Various mould profiles with different tapers were studied and some quality problems with a C_{eq} (carbon equivalent content) in the range of 0.27 – 0.40 % were solved using mould profiles with lower taper. The use of a "parabolic-like" profile modifies the shape of the gap between mould and steel realizing a better control of heat flux.

[EU-41.] (*SOLIMOULD*) In this project, benefits have been recorded also in reducing the oscillation stroke and frequency on the caster from the original settings. Medium carbon grades (where shrinkage rates are low) also recorded a beneficial effect because of the reduction of mould level set points. Simple models have been developed to assess how the modification of oscillation conditions can affect initial solidification by altering the effective taper of the mould. It was also observed that the reduction of mould level set point (in case of complex taper) is beneficial since binding effects in the mould have been reduced and low frequency level disturbances have been eliminated.

The study of mould taper was presented also in another project [EU-51.] (*Control of the dendritic structure of the initial frozen shell in continuous casting*). Two alternative geometries have been investigated. The main objectives are the prevention of the detachment of the solidifying shell from the mould surface and the reduction of the asymmetry of the solid shell thickness that gives rise to corner defects. The modelling of new geometries has been performed to identify the ideal mould profile. The shell is subjected to a strong contraction in first few centimetres below the meniscus while in remaining of the mould the displacement curve is less steep. Such a behaviour of the solid layer requires the use of a parabolic taper, which better fits the shell contraction along the whole mould length.

Finally, in [EU-40.] (*CASTEDESMON*) the influence of taper was studied for bloom product. Inadequate taper in the upper part of the mould, can lead to longitudinal cracks and depressions, occurring around the perimeter of round blooms (and at the narrow face of slabs). The most critical area for the formation of the steel shell is the one under the meniscus: in round bloom casting, possible mould distortion leads to a strong reduction of the taper at the meniscus, worsening the mould performance with respect to the surface quality of the product.

3.3.2 Sub-topic 3.2: Operating conditions

The optimization of casting parameters can be done with a deep understanding of the relationship between surface defects and casting variables. The parameters that can be adjusted are various and most of the times have interrelated each other. The optimization pattern that has to be followed needs to be supported by numerical and physical modelling of the process in order to identify a suitable operating window. Moreover, optimization of casting parameters often allows to set and define a worthwhile system of defect prediction with possibilities to downgrade rules due to potential crack generation. The mould and its thermal flux can be considered the core of casting process where all the variables have to be selected in order to ensure process safety, and adequate quality of the final product.

- Slab

Conventional and thin slabs with the presence of Ti or Ti+Nb are crack-sensitive due to precipitation of Ti, Nb(C,N) compounds during cooling. [EU-39.] . Prevention can be done by optimization of chemical composition or by modification of cooling strategy. In that case, thanks to the use of an ad-hoc simulator, it was possible to explore and test various cooling patterns. It was found that faster cooling is less detrimental for the analysed steels. For thin slab casting instead improvement of surface quality is attributable also to characterization of the passing to the equalization furnace.
The influence of Nb and Ti on surface quality is also faced in another project. In particular, since their preferential precipitation sites at grain edges, in particular at slab off-corner, an innovative soft cooling strategy was implemented [EU-43.] (*PRECIPITATION*). The temperature of the broad face of thin slab with different widths was kept above 900 °C. The segregation of Nb was mitigated, and improvements in term of transverse crack were achieved, more significantly for smaller thickness.
Transversal and star cracks have been investigated in [EU-44.] (*DEFREE)*; quality problems of the slabs were reduced adopting a nickel coating of the mould surface and through identification of the influence of superheat and casting speed. Moreover, significant improvements have been obtained by optimization of the roller settings of the caster in order to better fit the natural shrinkage of steel. This involved a remarkable decrease of centreline segregation severity.
[EU-48.] (*PMAP*) faced the hot ductility induced by Boron content into microalloyed slabs. The influence on precipitation distribution of microalloyed particles of various bending/straightening configurations has been studied the hot ductility of micro-alloyed steel grades is related to the time where precipitation is produced and to the strain rate: both the topics depend on the unbending radius. Unfortunately, during the experimental campaigns carried out during the project no influence of different bending/straightening configurations on precipitation distribution of microalloyed particles has been detected.
The observation of segregation phenomena and especially of cracks induced by segregation contributed to the understanding of oscillation mark formation [EU-52.] (*Determination of high temperature surface crack formation criteria in continuous casting and thin slab casting*). The study of distribution pathway led to say that oscillation marks are formed during the first steps of solidification. The formation mechanism is related to the friction between mould and strand shell. The segregated crack length depends instead on the ratio of oscillation mark width and initial depth. Border-cracking is reduced with increasing depth and narrowness while centre-cracking risk rises under the same conditions. It is suggested that border-cracking is influenced by the sticking of strand shell and mould wall. These considerations have been applied in the study of reduction of oscillation marks, depending on the mould oscillation strategy: the depth of oscillation marks increases at low casting speeds. The influence of casting speed on oscillation mark depth depends on the oscillation strategy.
On thin slab caster, oscillation marks are very shallow, because time for oscillation mark formation is lower than for a standard slab, since higher casting speeds and higher oscillation frequencies are used. Experimental campaigns revealed also that increasing grain size increases steel cracking susceptibility

[EU-52.] (*Determination of high temperature surface crack formation criteria in continuous casting and thin slab casting*).

The shape [EU-50.] (*SUPSYSCC*) of current curve of the oscillation levels have been successfully adopted for the monitoring of CCM motors. Correlations allowed to develop a system of alarm able to check any break-out occurrences and on-line checking of the machine status. Automatic and massive feedback about defects permitted in several cases the optimization of the slab downgrading rules.

The real-time monitoring of the shape of the mould together with communications about the performance was adopted in [EU-40.] (*CASTDESMON*) for the early detection of product quality. The study on the minimization of critical stresses on the steel shell led to a modification of the mould oscillation pattern into a non-sinusoidal movement. The system could be also used to define a new taper design for product quality optimization.

Another important aspect that was overlooked in [EU-41.] (*SOLIMOULD*) is the control and optimization of mould level. Its variability is directly related to end-plate taper variations, steel shell formation, heat transfer in the mould itself. In turn, mould level is related to the movements of the strand surface. The surface movements at each roll are synchronous, so the effects are additive and large mould level variations can occur. Argon flowrate in the stopper rod also influences the mould level as well as the carbon content [EU-41.] All these aspects affect the surface quality of the product. Hypotheses have been formulated to better understand the mechanisms and various experimental campaigns have been carried out; mathematical models were used to define the optimal operative conditions. Modifications on level control system let to reduce level deviations due to bulging. It detects regular frequencies in the mould level signals and applies corrective actions to the stopper. Trials indicate a reduction up to 30% in level fluctuations, but the system has been judged not sufficiently robust for a continual use.

The analysis of previous RFCS project put in evidence also the correlation between mould wear and surface defects [EU-40.] . Simulations and new monitoring systems led to the derivation of mechanisms for the evolution of wear patterns. Monitoring the extent of mould plate wear on the casting machine can allow to optimise the timing of mould change. Inside the work, application of corrective actions to limit the mould wear and the avoiding use of excessive taper at the bottom of the mould, reduced the probability of surface and subsurface cracking in slab casting.

The development of a new method to on-line measure the real taper during casting led to a better comprehension of the actual mould shape and the solidifying strand [EU-40.]

Statistical investigations between mould level signals and the generation of slivers, including multivariable analyses, showed that a moderate increase in the variance of the mould level signals is connected to an increase of generated slivers, although the variability for different sliver classes is very poor [EU-40.]

Finally, some studies have been done on some phenomena “outside” the mould. Optimization of Argon flowrate inside the tundish led to an improvement of casting conditions; the flowrate of the argon through the stopper can influence the clogging occurrence inside the tundish [EU-47.] (*DIRECT DEFECT TOOLBOX-DDT*). The problem related to loss of the first slab during the tundish change on peritectic steels was also analysed. It can be due to lubrication issues during the first meters of casting after a flying tundish change. So it was proposed to increase the amount of treated steel in tundish using extra scrap or to use of two layer covering material in tundish or to focus attention on the mould powder [EU-47.]

The influence of mould powder falls in another topic of VALCRA project. However, as reported in [EU-42.] (*SLAGFILMOUWL*) the tests of various powders in term of melting rate and various mould section size, led to the optimization of SEN design and to the development of high-speed cooling practice. Surface quality was improved.

The study of deep longitudinal cracks in special stainless steel wide slabs was faced in [EU-42.] . That class of steels are susceptible of longitudinal cracks in the region of SEN due probably to a lack of molten slag in that area (so called dry casting). Modifications of powder viscosity and adoption of low heat flux for "soft cooling" led to an improvement of surface quality. In that way, the differences in shell formation and in turn the associated stresses are minimized. Moreover, it was found that higher superheat (to enhance the temperature in the SEN region) and lower oscillation amplitude have also a beneficial effect on crack formation.

- Billet

Half-way cracks and off-corner cracks were detected in transversal samples of Nb microalloyed steel billets. The half-way cracks were related to reheating of the billet at the exit of the secondary cooling [EU-43.] (*PRECIPITATION*). A new water distribution was designed in order to avoid reheating; moreover, it was found that the adoption of new secondary water-cooling curves (with the same total amount of water) distributed with less water in the first zone implies a more uniform cooling.

In presence [EU-44.] (*DEFREE*) of C-Mn-B-Ti steels, a coarse austenite grain grows at the surface. The presence of nitrogen, aluminium and boron induced a low hot ductility during bending, resulting in transversal cracks in the billet corners. A method [EU-44.] to prevent transverse cracks is to avoid that bending and straightening occur at a temperature within the brittle temperature range of the material. The due changes of the secondary cooling pattern were adopted. The new practices have been applied with good results. But it was found that the current pattern of secondary cooling could induce the craze cracking when the steel contains high level of tramp elements as Cu, Sn, and As. Surface temperature was kept low enough to avoid formation of AlN with its effect on lowering ductility.

Decrease of macro-segregation in microalloyed and high carbon billets (and of the occurrence of transversal cracks) has been achieved by decreasing the amount of water and by applying hard cooling on the secondary cooling zone [EU-44.]

When hard cooling is used to control segregation, it was observed that there is a risk of intergranular cracks as well as surface corner defects. In that case, the secondary cooling spray nozzle type and arrangement has to be controlled [EU-46.] (*ICCRACK*).

The control of secondary cooling has been also faced in the project [EU-50.] (*SUPSYSCC*). An empirical surface quality index was defined and correlations between the secondary cooling parameters and the billet surface quality index have been identified. Through the development of various mathematical models, it was possible to check the effect of the casting speed on the surface temperature of the billet: casting speed has a stronger influence than the secondary cooling water flow rate. The developed digital system has been correlated with images coming from video-camera surveillance system installed on secondary cooling chamber: it was possible to acquire useful information in order to predict quality downgrading.

The definition of high speed casting practices, that increases productivity without reducing surface quality was faced in [EU-42.] (*SLAGFILMOWL*). In that case, studies on new powder composition and characteristics (viscosity and melting rate) have been used to modify the heat flux inside the mould. A mould friction index was defined to assess the efficiency of lubrication between mould and powder. It was found that at higher casting speeds, the heat flux was higher in the lower part of the mould, giving rise to the lower shrinkage, more contact and so larger friction. Automatic powder feed system was optimized. After several tests, and in connection with the implementation of mould powder consumption system it was possible to define a suitable operating window for high casting speed.

The definition of optimal operating window was faced also for bloom product during [EU-42.] Mould taper, casting speed and powder viscosity have been considered to set a numerical model. Simulations offer suitable solutions that have been tested on the plant and on various steel grades. It comes out that low-C steels (included peritectic steels) have great tendency to shrink, so an increase of casting speed or adoption of powder with increased viscosity are recommended to improve the surface quality. For high-C steel, the optimum conditions seem to be the opposite. Finally, the value of mould taper should be adjusted to ensure a uniformity of mould heat flux.

3.3.3 Sub-topic 3.3: Injection techniques

The present sub-topic encloses the technologies to exploit the concept of grain size control by means of dispersoid inoculants placed into the steel microstructure. That goal can be achieved through the identification of the optimal inoculant materials and optimal addition techniques for steel continuous casting. The inoculant materials work as grain refining with dispersed non-metallic inclusions of defined size. The only RFCS project that faces with that technology is GRAINCONT [EU-45.] . Thermodynamic considerations allowed to identify potential inoculants. Various tests at laboratory scale have been performed; the first results show that addition of Ti+Ce in molten Fe-20%Cr leads to the formation complex oxides with Ti, Ce and Cr, while addition of Ti+Zr in molten Fe-20%Cr results in primary precipitates of ZrO2 and ZrO2+ZrN. ZrN represents a potential nucleation site for α-ferrite during solidification, which gave a significant grain refining effect, its effect being directly related to the number of particles that are formed. Injection tests have been performed also with Fe-Ce powder.

Other tests have been performed with Fe-TiO2/TiN and CeAlS additions: the main aim is to obtain very fine exogenous sulphides and oxide particles in liquid steel to refine the solidification and final structure. The project focuses also on the study of suitable injection system to be implemented at industrial scale. A pre-existing injection system (Hollow Jet Nozzle concept) was selected as "base" technology. During the project, some modifications have been applied in order to increase the flexibility of the system. A

mechanical flexible screw conveyor was used. The system was able to manage a wider range of powder size and a larger amount of powder.
At the end of work, comparison between various inoculants showed that the Fe+TiO2/TiN pellets/cylinder additives have a better behaviour than Fe-TiO2/TiN powder in term of grain refining.
Moreover, the modified "Hollow Jet Nozzle" has been proved to be a mature and reliable injection technology and industrial trials could be faced.
Ti+Zr seems to be a promising inoculant system for grain refining of ferritic stainlesssteel grades.

3.3.4 Sub-topic 3.4: Improved steel compositions

The relationship between steel chemical composition and occurrence of surface defects on the final products was deeply analysed in various RFCS projects. The major source of surface defects (e.g. transversal and off-corner cracks as well as internal defects) is the presence of elements into the steel susceptible of edge grain precipitation (micro-segregation) with consequent formation of brittle phases. When the product is strained (bending for example), there is high risk of surface damage.
Improvement of steel composition is related to the understanding of precipitation mechanism: the elements that play an important role in that phenomena are mainly V, Nb and Ti. However, the possibility of optimizing the chemical composition of a steel is strongly limited by the specifications on every steel grade. Other possible countermeasures to manage the precipitation during casting is to control at the same time the cooling path.
Presence of inclusion or tendency of the steel to form incrustation are equally analysed in that sub-topic.

- <u>Slab</u>

[EU-39.] (*Castability and surface quality of steels microalloyed with Ti or TiNb in continuous casting of thin slabs and beam blanks*) The presence of Ti and Nb influences the formation of crack surface due to formation of edge-grain precipitates. The problems related to the presence of Ti and Nb are the possibility to form detrimental compounds such as TiN and Ti, Nb(C,N). Thermodynamic calculations and SEM+EDX analysis are the main tools used to investigate the precipitation inside the slab. It comes out that the presence of TiN or TiC depends on Ti content. It was assessed that TiC can precipitate on pre-existing TiN or as fine particles. The main mechanism of fracture is trans-crystalline shear fracture.
The analysis also shows the presence of TiCS compounds with alumina and small amount of TiCN. The first one is influenced by sulphur content, the second one is also influenced by Mn content. Optimal chemical composition was studied in connection with the definition of casting conditions. In thin slab, hot ductility is better when Ti is added to Nb, with a cooling rate that leads to a preferential precipitation of Nb(C, N) on TiN. So before modifying casting conditions, it is important to set the optimal Nb/Ti ratio, and C, S and N. Experimental trials showed that low cooling rate from solidification and high temperature of strand bending and unbending are required. Concerning the cooling rate between equalization furnace and rolling mill, trial heats showed that hot ductility slightly improved with slow cooling rate for Ti steel, instead, for TiNb steels, benefits are expected for high cooling rate.

The project [EU-52.] (*Determination of high temperature surface crack formation criteria in continuous casting and thin slab casting)* was focused on the study of cracks on oscillation marks, perpendicularly to casting direction in connection with some segregated cracks that lay along the primary δ/ γ grain boundaries and that are formed during solidification. The depth of oscillation marks has also been studied in function of carbon content of steel: ultra and low carbon range is critical, because the solid shell can easily deform itself; it includes also steel in the peritectic range (i.e. between 700 to 1200 ppm of carbon) because the δ→γ phase transformation causes high shrinkage that promotes the formation of deep oscillation marks. Medium carbon steel with low Ti contents instead presents a greater sensitivity to softer cooling in comparison to the Ti-microalloyed steel grade. This implies that Ti additions have a positive effect on surface cracking. On the other hand, the project proved that the presence of cracks on oscillation marks can be avoided with proper cooling strategy.

The slabs with a significant amount of Nb are more susceptible to segregation and transverse cracking [EU-43.] (*PRECIPITATION*). The variation of V/Nb ratio together with new soft cooling strategy can contribute to improve product quality: the temperature of the broad face of small thickness slab should be kept above 900 °C to avoid drop of ductility (especially in the corner regions). Reduction of transverse cracking is more relevant for smaller thickness.

The project [EU-48.] (PMAP) considers the influence of Boron in Nb and V microalloyed steel. For some microalloyed steel grades the distribution of both the Ti/Nb and boron rich precipitates is different for cracked samples and non-cracked samples: a hypothesis is that there is a modification of grain boundary ferrite distribution as boron affects the ferrite formation. The reduction of ductile grain boundary ferrite would increase the tendency of the material towards intergranular fracture. Within the same project, it was found that the effect of Boron on austenite decomposition is similar to an increase of the cooling rate, or to an increase of the austenite grain size, and so related to an increase of transformation stresses. The detrimental effect of Boron is quite relevant during tertiary cooling. Possible countermeasures that have been investigated are:

- Presence of Ti mitigates the TSC (Thermal stress cracks) problems producing early formation of big TiN which avoid the precipitation of more dangerous AlN or BN
- Different design of the secondary cooling intensity
- Decreasing the distance between the consecutive cooling zones. If not possible, it could be convenient to enhance the casting speed in order to limit the reheating time of billet surface

[EU-48.] High amounts of Cr and Mo in microalloyed steels with Nb+B+V have a large influence on microstructure during tertiary cooling; low Ti and high Al content instead could induce the formation of small AlN precipitates. Laboratory studies and numerical simulations stated that BN precipitation can occur on MnS particle. So, for these steel grades it is important to maximize the ratio Mn/S. The MnS secondary precipitation also enhances the hot ductility: the studies put in evidence that optimized hot ductility properties can be obtained when all the sulphur compounds precipitate in the interdendritic liquid and ideally there is no residual S in solid solution for producing secondary precipitation in the solid.

- Billet

The billets report almost the same problems of slabs in term of segregation and type of precipitable elements (Nb and V). Also, Boron has an effect similar to what is presented for the slabs. In the project [EU-48.] the hot ductility in Boron containing billets was studied: it was shown that the presence of sulphur enhances the detrimental effect of Boron. In the frame of finding the optimal chemical composition, it was defined a critical value of Mn content: for Mn < (Mn)c, B and S produce low melting interdendritic liquids, which are related to internal cracking. Big primary MnS and M2(B, C) precipitates have been also detected. Although the S content can be controlled with Mn, there is not a method for controlling the B enrichment. To avoid billet internal off-corner cracking in B steels, modifications of casting parameters, for example casting speed, mould taper, foot roll adjustment, are proposed. To avoid the billet internal half-way cracking, straining of the billet surface during reheating should be prevented/limited.

The phenomena of Thermal Stress Cracking (TSC) were observed for the billets with the presence of microalloyed elements. The billets with high Mn combined with high Cr or high V steel grades show significant TSC [EU-43.] (*PRECIPITATION).* High Mn and/or Cr contents decrease the austenite/ferrite transformation temperature, thus enhancing precipitation of V(C, N) or AlN before transformation starts; precipitated particles with the austenite phase has high crack sensitivity if strained. Inside the project, an increase of TSC caused to Bi and Pb (due to their effect on temperature ductility) is reported. The partial substitution of V with Nb was also proposed and tested; however, the grain size is affected by the presence of Nb, with an undesired effect on mechanical properties.

A second aspect of the optimization of a steel grade was the study of the 'link casting effect' [EU-43.] The analysis on different billets showed that link casting is particularly harmful for medium carbon and high manganese microalloyed steel grades. It produces a large number of deep cracks. Hence, link casting should be avoided for those grades.

The presence of Ti in the billet has been investigated in [EU-44.] (*DEFREE*). C-Mn-Ti steels are characterized by a surface containing a coarse austenite grain size: high N contents induce a consistent AlN precipitation along the grain boundaries. Under a low strain rate at bending point, the surface is subjected to embrittlement along the austenite grain boundary. In that case, it was found that the best solution is to avoid the formation ferrite along austenite grain boundary by optimization of cooling strategy.

Finally, as said above, chemical composition influences also the inclusion panorama inside the steel with consequences in castability. In particular, Ti containing steels have been investigated in order to evaluate the content of inclusions and possible castability problems [EU-39.] : no correlations have been detected between inclusions and castability. However, it came out that a reduction in casting speed is often associated to oxide incrustations on the inner wall of the calibrated nozzle.

3.3.5 Discussion and last developments

The optimization of continuous casting process involves many aspects of the plant and most of them are related together. It means that the modification of a single parameter implies the assessment of its influence on other process variables. As reported in the analysis of RFCS state-of-art, mathematical modelling and development of simulation path have an important role in the approach to the problem. Many RFCS projects focus attention on the analysis of steel chemical composition and how it influences the presence of defects on surface quality. In particular, it regards all the steel grades where the presence of certain elements led to a local precipitation of detrimental compounds, mainly V, Nb, Ti and B containing steel. The precipitation is influenced also by the cooling pattern inside the mould, but as it was pointed out, it cannot be completely removed. For that reason, a preliminary study of chemical composition and how it can be varied (with the related mechanical properties and acceptability range bounds) is strongly recommended in order to limit detrimental segregation issues. From the analysis of RFCS works, it emerged that the problem is much more relevant for flat products than long products.

The monitoring of cooling strategy has to be taken into account in order to ensure the adequate steel shrinkage and the formation of the target microstructure. Optimization of cooling strategy involves the water flowrate for heat flux removal inside the mould and the control of secondary cooling. The influence of oscillation mould and mould level is also analysed. One of the most useful practices could be the control of off-corner temperature for microalloyed steel slab. The strategy consists in controlling the temperature in order not to fall in the ductility drop range. The precipitation of Nb, V or Ti occurs predominantly at the edge of the slab, producing brittle phases: at bending, the slab is subjected to strain and there is the risk of cracks.

E Erdem et al [7]proposed the development of a digital model able to simulate the solidification of the strand in order to optimize the cooling strategy. The work is done for three steel grades that are affected by edge corner precipitation of V carbonitride. It emerged that precipitation kinetics have influence on crack sensibility.

For billets, in general, the most studied method to control the incidence of the surface defects is the adjustment of secondary cooling (definition of optimal water nozzle design). Yanshen Han et al [8] analysed the thermal soft reduction (TSR) of billet. A validated mathematical model was developed to simulate the thermal behaviour of continuous casting billet. According to the model, the position and water flow rate were optimized in order to position the TSR at a certain level under the meniscus. The optimal position was selected considering where the temperature of the billet centre dropped below a value such that the mushy zone becomes rapidly impenetrable to liquid. Experimental trials showed an improvement in the central porosity, V segregation and central segregation.

Central segregation was recently faced by An H. et al [9] They proposed a complex electromagnetic stirring technique (M+F-EMS) and low superheat pouring to increase the equiaxed crystal zone and fine equiaxed grains for high carbon steel blooms. Numerical investigations and experimental trials revealed that the central equiaxed crystal ratio and the centre segregation can be enhanced under optimized lower superheat and higher casting speed with M+F-EMS.

Gabelaya, D.I. et al [4] instead developed a method to calculate absolute and relative values of steel slab linear shrinkage in billet casting. The method includes the role of carbon and the distance from the metal surface in the mould on steel slab relative linear shrinkage. The simulation outcomes could be used in CBCM (Continuous Billet Casting Machine) design for the installation of a dynamic soft reduction system. The heat flux removal inside the mould is strictly related to powder properties. So, the correction of casting speed and cooling strategy has to be based also on the study of mould viscosity and melting rate. An inefficient powder can lead to the occurrence of a large number of surface defects (oscillation mark, transversal and longitudinal cracks, inclusions too). So, the casting parameters have to fit to the selected powder and the other way around. In controlling the activity of the powder, great attention has to be given also to temperature of steel (superheat) and mould oscillation that is necessary to ensure proper powder infiltration.

The characteristics of mould powders have been also analysed in recent works. Zhang, X. et al [5] promoted a mathematical model to study meniscus solidification and slag infiltration in the mould. The model also involves the monitoring of heat transfer, solidification of the steel and mould oscillation. The main output is the growth of steel shell. It was found that the increase of casting temperature and casting speed as well as a reduction of water flow in the mould and of oscillation magnitude could reduce the solidified depth of the meniscus on the inner part of the mould. This influences the slag infiltration and the formation of oscillation marks.

Wang, X. et al [6] investigated the mould oscillation and its influence on lubrication and mould friction. They developed an online measurement system for mould friction, design of negative oscillating parameters and powder consumption. Moreover, the effects of three different control models including sinusoidal and non-sinusoidal oscillation modes on mould friction and powder lubrication have been studied. The combination of inverse control model and non-sinusoidal oscillation mode can ensure a proper powder consumption, a suitable effect of friction force on strand surface, especially for high speed continuous casting. The proposed method can be seen as basis for driving and optimizing mould oscillation among control models, sinusoidal oscillation and non-sinusoidal oscillation.

Improved caster design has been a subject of the present topic. Despite the high potential of the technology, few solutions have been explored. They concerned in particular the groove pattern inside the copper mould and taper design. The second one recorded a discrete level of success and spread, probably related to the easiness to operate such a modification. Other innovative layouts found issues related to their spread, probably since the high cost of investment.

All the RFCS projects point out that there is not a general recipe to optimize a process. The individuation of best practice depends on a multitude of casting parameters and process needs (productivity, incidence of defects, plant layout, steel grade etc.): so, they have to be appropriately selected with a preliminary study.

Based on the quantity and quality of results achieved in RFCS project, this scientific approach is proposed: study of initial conditions, setting of mathematical models, identification of suitable process features and experimental testing.

The level of detail of the mathematical models is not always defined. Most of times, it is built to study a specific area of continuous casting plant, and to give a specific output. The outputs often regard other casting parameters or indications about steel microstructure evolution: they have to be correlated to the presence of defects on the final product and this still represents an object of study.

3.4 Mould powders (Material Processing Institute)

Mould powder or mould flux has five main functions in the casting process: Thermal insulation, prevention of reoxidation, absorption of inclusions, lubrication and facilitating uniform heat transfer (Figure 3-10). Powders are applied to the surface of the casting mould either manually or using some kind of automated feeder. The powder then forms a number of layers each of which performs one of the functions listed [160].

The powder when applied is distributed across the surface of the mould to form the first layer of loose

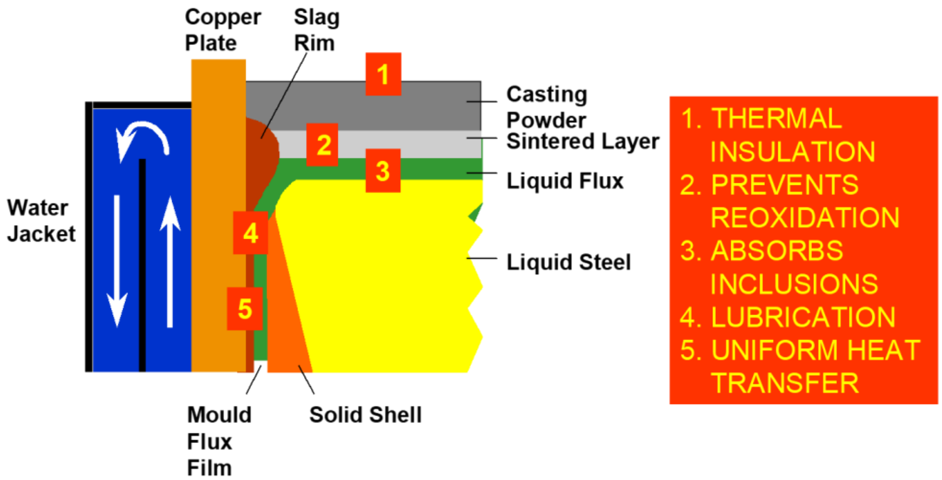


Figure 3-10:Schematic showing the different layers of Mould Powder/Flux in the casting mould

powder. Heat transferred from the mould causes the underside of the loose powder layer to sinter into a crust which then melts to form the third layer which is liquid flux. Liquid flux then penetrates between the solidifying strand and the mould face flowing down with the strand. A layer of solid flux is formed where the liquid flux comes into contact with the water-cooled mould. This tends to form a thick rim around the liquid pool at the meniscus leading to a thinner layer which extends down the mould face. The liquid layer flows with the moving strand but the solid rim and attached solidified film tends to stay in place.

The top layer of raw powder and the sintered layer provide two of the desired functions. Firstly, it provides thermal insulation preventing heat loss from the top surface. This is desirable for the solidification of the strand to form in a controlled manner within the mould. The insulation ensures that the top surface of the molten metal does not begin to freeze which could lead to bridging between the solidifying strand and the metal feed tube. Secondly the liquid and solid layers form a barrier to the atmosphere preventing oxidation of the liquid steel which could lead to the formation of inclusions and other quality issues.

The next layer, the liquid flux layer, also has two functions. Inclusions carried through the SEN to the mould in the form of mainly alumina (Al_2O_3) tend to be buoyant in the liquid steel helped by the application of inert gas and careful control of the flow patterns in the upper mould. This results in the inclusions being transported to the surface where they are captured by the liquid slag. The inclusions are then dissolved into the flux [161]. Any inclusions or gas bubbles coming into contact with the solidifying steel shell will be captured and held within the product potentially leading to quality and defect issues. The second and more important function of the liquid layer comes where it flows down between the strand and the mould which is promoted by the oscillation of the mould. This layer provides lubrication between the solidifying shell and the mould. This lubrication prevents sticking and reduces the effect of friction on the very delicate initial solidifying shell.

The final layer, the solid flux layer, forms a thermal barrier which controls the horizontal heat transfer between strand and copper mould. The heat transfer rate is controlled by the thickness and thermal conductivity of the film and the composition. It is essential that uniform heat transfer is achieved especially during the early stages of solidification as the majority of surface defects are initiated in this region.

The analysis of the impact of European research on the understating of mould powder influence on the crack formation will be described by grouping the main results into three categories: powder composition, physical properties and mould feeding system.

3.4.1 Powder composition

Standard mould powders are a mixture of glassy components and basic oxides which solidify to form a semi-glassy slag. They have a base composition made up of calcium oxide (CaO) and silicon dioxide (SiO_2) accounting for up to 70% of the mixture. Other components include oxides of magnesium (MgO), aluminium (Al_2O_3), sodium (Na_2O), potassium (K_2O), titanium (TiO_2), zirconium (ZrO_2), boron (B_2O_3), lithium (Li_20) and manganese (MnO). There is typically a fluoride content (CaF_2 or NaF) which acts as a fluidising agent and to promote crystallisation of cuspidine ($3CaO.2SiO_2.CaF_2$) which readily forms during continuous casting due to its low activation energy. The degree of crystallinity has a significant effect on the heat transfer properties.[162].

The composition of a mould powder can alter during casting particularly the alumina content as alumina inclusions are absorbed by the liquid flux (*INNOSOLID*) [EU-53.] , [163]. Experiments have shown that during a cast the alumina content of a liquid slag film can increase significantly but may not necessarily alter the viscosity of flux depending on the slag phases formed. In other conditions the change can make a more significant difference.

In addition to the slag components, carbon is added to control the melting rate. The amount, particle size and form of carbon added has an influence on the melting rate. More carbon will reduce the rate, also the coarser the carbon element, the slower the reaction. Low carbon mould powders prevent pickup of carbon from the mould powder when casting low or ultra-low carbon steel grades.

During project [EU-58.] (FLUXFLOW) it was found that for stainless steel, a higher content of free C increases the occurrence of defects. This appears to be due to the influence of the C-content on melting rate and thus on liquid flux layer thickness. A similar observation could be made for the long products. It was also seen that the thickness of the flux layer depends strongly on the powder used. This can lead to entrapment of powder which has a great impact on the occurrence of defects remaining on the steel surface. Studies into steel superheat have concluded that the thermo-physical properties of the casting powder work well within the usual temperature range of the steel. However, if the superheat exceeds approx. 25°C, an increase of entrapment seems to occur for carbon steels.

Slag entrapment is a significant quality issue for strip steels and billets cast at high speeds. Slag becomes trapped on or in the surface of the strand at the meniscus when in-mould turbulence and metal flow velocities are high due to high casting speeds. Techniques for reducing entrapment include optimisation of the metal flow conditions through careful design of the SEN, SEN immersion depth, Argon flow, Electromagnetic Breaking or to increase the viscosity of the mould slag. Increasing mould slag viscosity results in a decrease in the ability of the slag to lubricate the mould which in turn leads to increased surface defects such as longitudinal cracking, sticker break outs and star cracking [EU-54.]

Casting speed has an effect on flux entrapment. [EU-58.] . The velocity of liquid steel in the mould can be directly linked to casting speed. Not only the absolute value of the horizontal velocity near the interface between steel melt and liquid flux has to be taken into consideration, but also its fluctuation. For high casting speeds the liquid flux layer thickness is increasing. The fluid flow in the mould also changes when a change of SEN geometry occurs along a casting sequence e.g. due to clogging. To assess the impact of such a deterioration in flow on entrapment, a characterization of clogged SENs was used in a numerical model. It has been seen that, when clogging occurs, it tends to concentrate around the SEN ports, in the well, and in the stagnant region of stream bifurcation. Larger SEN port leads to lower RMS-values concerning the horizontal flow velocity at the steel/flux interface. Moreover, the horizontal flow velocity is less sensitive with regard to SEN immersion depth. It was found that the flux layer thickness decreases with increasing immersion depth. In case of carbon steel, the SEN immersion depth within the current operational practice does not significantly affect the level of entrapment for the range of values studied.

It has been suggested that non-Newtonian mould flux could be used to reduce the occurrence of slag entrapment [165]. In this case, the flux unlike a standard powder has a viscosity that varies with the shear force applied and thus can have a high viscosity at the meniscus reducing entrapment and low viscosity between the stand and mould where lubrication is required. The ongoing NNEWFLUX [EU-54.] project aims to study this effect.

In the project [EU-58.] , long product properties were analysed. The powder properties of most concern were the viscosity and the melting rate which should be properly coupled with casting speed. In particular, the carbon content, which melting rate depends strongly on, played a significant role. The lower the steel grade carbon content, the higher the shell shrinkage. To compensate for this greater liquid slag production is required. To achieve that, low values of free carbon content were used to provide a higher melting rate and a homogeneous slag film between the mould and the solidified shell. The recommended content was found to be below a critical value. This critical value is 5% for stainless steels and 20% for carbon steels, respectively. For the higher carbon grades, the mould flux viscosity should be lower to improve liquid flux infiltration between billet and mould. The work indicated that an optimum value of viscosity should be the casting speed in m/min multiplied by 3 in poise. A further operating parameter related to slag entrapment was found to be the oscillation stroke length (related to powder consumption). If higher (in the investigations related to billet casting at Cogne Acciai Speciali (CAS), exceeding 8 mm) the risk of such a defect is higher than that achievable by almost doubling of the EMS coil current.

Mould powders of different thermophysical properties were used for trials on an industrial slab caster of Corus during the casting of peritectic C Nb and Ti microalloyed steel grades [EU-60.] (*PRECIPITATION*). The data collected from over one year of the industrial trials revealed that it is not only the basicity, but an optimum combination of basicity and viscosity of the mould powder that is essential to change the carbonitrides precipitated at the surface within the mould for an optimum surface quality of a specific steel grade. The measurements of the effect of mould powder layer thickness on steel shell thickness did not show a conclusive relationship for different steel grades. However, it was shown that steel shell thickness, irrespective of steel chemistry, decreases more sharply when layer thickness increases for the less basic powder. No clear relationship between precipitate size and morphology was established with mould powder chemistry and mould powder layer thickness.

A study was carried out on the effect of sulphur content on the meniscus fluctuation and surface quality i.e. the higher the sulphur content the poorer the meniscus stability. [EU-61.] (LSSEMIQUAL) Top slag analysis from industrial trials highlighted that the choice of powder with respect to surface quality and cracking is important but no details were given.

A number of novel or specialized mould fluxes have been used in the casting process. As mentioned previously When casting low or ultra-low carbon steel grades pickup of carbon from the mould powder can be a problem which can lead to surface defect issues. Low carbon mould powders help prevent this, but without enough carbon in the mould powder, the melting rate becomes too high and can cause slag rim issues.

The use of fluorides in mould powders to control crystallinity, although extensive has significant negative aspects. When fluorides react with cooling water hydrogen fluoride gas is given off that has potential to cause health and safety issues for operators in the immediate area and environmental issues on the larger scale. Other by products such as hydrofluoric acid lead to issues with corrosion in the casting machine. A kinetic study on the fluoride evaporation has shown that the fluoride gas emissions occur when the samples are present as liquid phases. The type of fluoride gas is determined by the chemical composition of the casting powders, while the percentage of emissions depends on both the viscosity and surface tension of liquids. [163] There are ongoing projects looking at the selection of suitable low fluorine or fluorine-free powders. The main thrust is the replacement of the fluorine bearing elements with an alternative such as Na2O or B2O3 [164]. In trials these have been shown to perform in a similar manner to conventional powders for specific steel grades. There was also an associated benefit noted that the erosion of the SEN where the slag layer interaction with the refractory seemed to be less than with conventional powders.

3.4.2 Physical properties

In order to understand how a mould flux will behave during casting it is important to understand the physico-chemical properties of the mould flux which include:

- Viscosity (η) - A measure of how resistant a liquid is to movement. The viscosity of a mould flux ix usually quoted at 1300°C which is within the temperature region that it operates during casting
- Liquidus Temperature (T_{liq}) – Temperature at which the flux is completely liquid.
- Solidification Temperature (T_{sol}) – Temperature at which the flux is fully solid.
- Break Temperature (T_{br}) - Temperature at which there is a significant change in the viscosity usually associated with the start of crystallisation.

These properties can be measured in the laboratory using a range of techniques such as heating microscope, rotational viscometry and simultaneous thermal analysis (STA).

Empirical rules have been developed to select slag properties (viscosity, break temperature) to provide the correct level of lubrication and horizontal heat flux (leaving the shell) for the given casting conditions to avoid casting problems like longitudinal cracking and sticker breakouts [169]. Figure 3 shows how of slag viscosity for slags used in the casting of slabs, blooms and billets varies with Break temperature (T_{br}) as a function slag viscosity

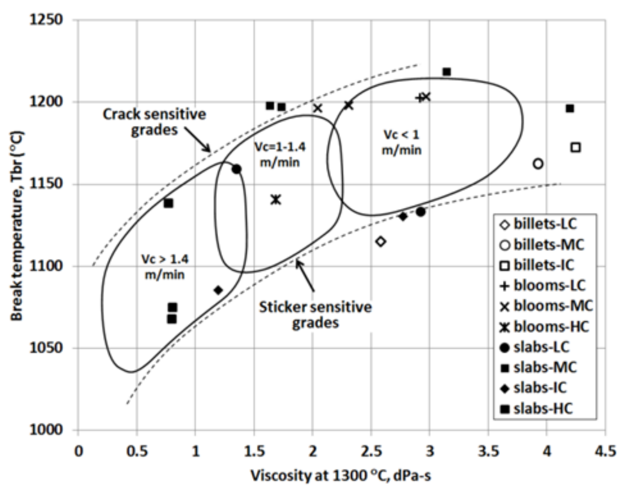


Figure 3-11: Break temperature (T_{br}) as a function of slag viscosity for slags used in the casting of slabs, blooms and billets [169]

Physical properties of a powder include mould flux, melting rate, powder consumption, heat transfer.

Melting Rate is simply the rate at which fresh powder melts to form liquid flux. Melt rate is important in that it must be sufficient to replace liquid flux consumed by the process.

Powder Consumption is closely linked with the lubrication properties of a mould powder. The depth of the flux pool increases with the casting speed and melting rate. The flux pool depth is dependent on the balance between the consumption rate and melting rate. If the melting rate is too high, it is impossible to maintain a stable layer of loose powder and if it is too low there will be insufficient liquid flux to lubricate the mould. It has been recommended that the melting rate of a powder must be sufficient to maintain a liquid slag depth of greater than the oscillation stroke length. [EU-59.] (*SLAGFILMOWL*)

Mould powder consumption is heavily dependent of section size of the product being cast [EU-57.] . The ratio of cross section to length of circumference can be accounted for in powder consumption measurement by quoting as kg/unit area or kg/tonne cast. The latter also compensates for casting speed. It has been shown that the consumption reduces with increased section size. The most direct influence on powder consumption was casting speed although a secondary correlation was established with carbon content and more significantly carbon equivalent. Other parameters such as superheat, argon injection rate and pressure, SEN immersion depth, surface to volume ratio of the mould, Ca and Al content of the steel and tensile strength of steel were investigated, but no significant correlations were found. The rates calculated from these correlations were used to control a new automated powder feeder with promising results, but more work was needed to optimise the system.

Models for predicting flux consumption were developed in project [EU-57.] (*Mould powder consumption, melting and lubrication and their effects on mould heat transfer and subsequent surface quality of continuously cast slab)*: the model used viscosity and melting temperature to determine temperature profile along the shell and mould surface and temperature and liquid/solid fraction through the slag film. From these the powder consumption was derived with good agreement with measured values. The model can be used to specify the melting range and viscosity required in a mould powder. The effect of oscillation strategy on powder consumption, the slag pool depth and the thickness of the slag film in the mould/strand gap and their consequence for heat transfer, lubrication and slab surface quality was also investigated via laboratory simulation. Following tests and modification, predicted shell thickness was in good agreement with the measured values and the correlation between measured slag layer thickness and the values predicted from powder consumption were greatly improved. However, many more data are required for a statistical analysis to improve the prediction formula.

The heat transfer from steel to cooling water passes through a number of layers. Liquid steel, solidifying mushy zone, solidified steel, liquid flux, solid flux, an air gap, copper and finally into the cooling water (Figure 3-6).

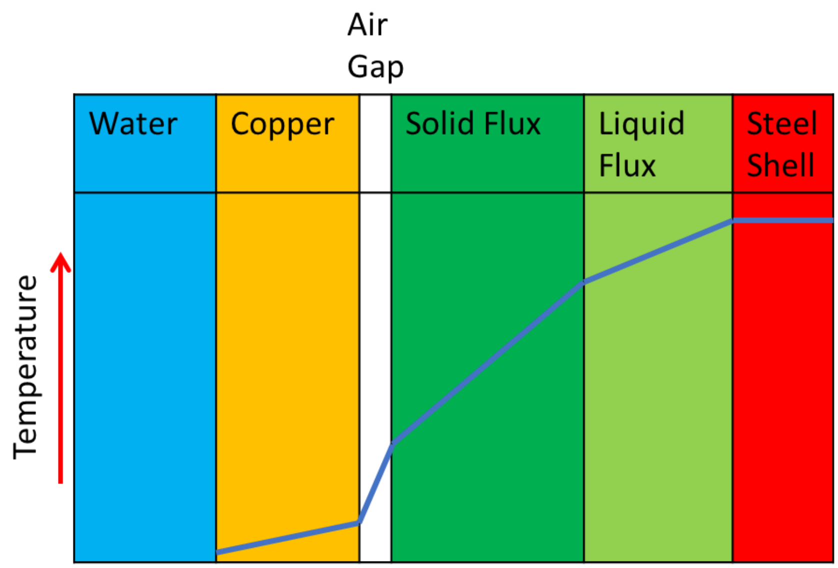


Figure 3-12: Schematic representing the heat flux from steel to cooling water in the continuous casting mould

Heat transfer through the flux layers is controlled primarily by the thickness of the layers and the amount of crystallinity in the layer. Basically, heat transfer through the liquid slag layer is reduced by the scattering effect of the crystal boundaries. Crystallization in the slag layers occurs in different manners. As the liquid slag cools, crystallisation begins at the break temperature with the formation of dendritic crystals within the liquid [167]. The investigation of glass/crystalline ratios in order to identify relationships between glass/crystalline ratio and thermal diffusivity has been performed [EU-57.] . These were used in the development of the model of heat flux in the mould. Powders showing significant differences in crystallisation tendency showed slight differences in viscosity, but large differences in thermal diffusivity, as determined by measurements carried out on samples taken from the mould (slag film and slag rim). Unlike published values, the values obtained here show a strong correlation with the glass/crystalline ratio. It was found that the thermal diffusivity of the slag film could be predicted from the glass/crystalline ratio provided that the prediction is limited to powders having similar chemistries and exposed to similar heat exchange conditions.

The influence of basicity on crystallisation rate in general has been shown and its impact on film thickness which in turn regulates the heat flux - the greater the degree of crystallisation the greater the film thickness [EU-59.] . A thermodynamic study of slag films collected during the project showed that two different crystal types can be found in the film. Close to the steel shell they are dendritic and an angular type close to the mould, formed as solid precipitation in the amorphous slag.

Many regard basicity (in a simplified form the Lime/Silica Ratio) as a measure of the potential degree of crystallinity in the flux layer. When specifying a powder, the basicity can be used as an indication of the likely thermal resistance in practice. However, the LUBRIMOULD project [EU-62.] suggested that the depolymerisation index (NBO/T) index is a better parameter for evaluation of the flux behaviour with respect to the commonly used basicity index. The depolymerisation index (NBO/T) is a calculated parameter based on the chemical composition of the casting powder [160].

A secondary method of control of heat flux in the slag layers is by absorption. It is known that certain oxides in the liquid mould flux e.g. MnO, FeO and NiO absorb heat rather than transferring it.

Another variable in horizontal heat flux is the air gap between the solid flux layer and the surface of the copper mould. There is evidence that as the glassy slag layer recrystallises there is an associated volume change which can lead to the solid layer shrinking away from the copper increasing the air gap. The greater the degree of crystallinity the greater the air gap therefore greater thermal resistance.

The effect of mould heat flux and friction variations on surface quality and breakouts for microalloyed billets has also been studied in [EU-63.] (*TRANSIENT*). A relationship between high mould friction, poor surface quality and breakouts was established. Plant trials with a lower viscosity mould powder (9.4 poise vs 12.5 poise) were carried out on 37MnV6S steel grade. Results showed that the lower viscosity powder gave consistently lower friction readings at the mould surface when running higher casting speeds in the range of 1.35 to 1.50 m/min and that off corner cracking was reduced. However, it was also shown that the mould friction measurements became more variable at casting speeds below 1.20m/min and there was a negative effect on surface quality when casting below 1.35 m/min using the lower viscosity powder. As a result of this work plant procedures were changed to use the lower viscosity powder for all microalloyed medium carbon steel grades and to maintain casting speeds within the range 1.35 to 1.50 m/min. It was also decided to avoid flying tundish changes on these grades and to stop strands rather than reduce casting speeds when logistical issues arise with the melt shop.

By considering billet/mould friction information together with the thermocouple signals from the instrumented mould in the [EU-59.] project, it was possible to observe slag rim formation in some cases. It was noted that there was an increase of the temperature close to the meniscus area and decrease of the friction signal which indicated the growth of the rim in the meniscus area. Friction and thermocouple measurements were useful in characterizing other transient phenomena in the mould including responses to additions of mould powder. Mould powders, slag rims and slag films from the mould strand gap and mould surface were characterized in the laboratories. Data obtained from this activity were used in the modelling activity of the project and for increasing understanding of the relationship between powder composition and powder behaviour. It was found that the key powder properties for their high-speed billet casting practices were viscosity and melting rate. An investigation of the chemical interaction between slag film and steel was carried out by analysing slag film samples taken from industrial casters together with the corresponding operational data. [EU-59.] The model is based on mould powder, slag and steel put in contact under thermodynamic equilibrium conditions at fixed temperature and reproduces the trend of the chemical variation in the slag composition. The model was applied to different casting conditions of Sidenor and the comparison with the experimental evaluation of slag film samples showed that, for slag film modification good agreement between calculated values and experimental values has been obtained in all the cases examined. In particular, steel metallurgy greatly affects the chemical composition of the slag derived from the mould powder, and it was been shown that the effect of the chemical interaction can be dramatically different for minor variations in steel composition.

Two novel methods of controlling the horizontal heat flux have been reported recently. Both are experimental and yet to be proven in the industrial application. The use of small number of pores and iron particles that form in slag films are known to contribute to reduction of heat transfer by the scattering of radiation. The first technique reduces heat transfer by applying an intumescent mould coating which forms a layer including controlled porosity [168]-[169] and the second uses increased number of iron particles in the flux to [172]. Both these are being investigated in new ongoing RFCS projects OPTILOCALHT [EU-55.] and RealTimeCastSupport [EU-56.] .

Another project which aimed to reduce the heat flux at the meniscus was the [EU-53.] INNOSOLID project. The aim of the project was to improve product quality with two innovative concepts for an optimized heat transfer for slab casting of ultra-low carbon (ULC) and peritectic steel grades:

- Local and dynamic cooling concept (*LDCC*) considering the local and dynamic control of heat transfer by adjustment of the design and flow conditions in the cooling jacket.
- Structured copper plate concept (*SCPC*) considering the adaption of heat transfer by application of mould copper plates structured with grooves.

The SCPC concept had a strong mould powder element. This application of a surface profile such as grooves to the mould copper surface. The profile allows the solidified slag layer to thicken locally increasing the thermal resistance in the grooved area. The slag film formation on a structured copper plate was investigated in the laboratory by VoesAlpine using a dipping test with a grooved probe cylinder. [EU-53.] . The results showed a significant influence of the viscosity, i.e. penetration into the grooves was increased with decreasing viscosity. It was observed that the non-grooved copper surface led to a more “uneven” shell thickness on the probe cylinder. It could be shown that local minima of the shell thickness correspond to local maxima of slag film thickness. The increase thermal resistance due to the bigger slag film thickness was judged as reason for this behaviour. The optimum surface profile was selected by numerical simulation and physical laboratory trials and then applied to the mould of a pilot caster at Tata Steel some success. However, it was not possible during the timescale of the project to move to industrial trials.

3.4.3 Mould powder feeding

Mould powder feeding is critical to performance of mould powders in terms of consistency and repeatability of the casting process. Manual powder feed performed by operators is the most basic method but is reliant upon the training, experience and attention of the individual operator to maintain a consistent cover on the mould. In reality this results in a batch feed process which means that powder level cycle and can range from a heavy "black" practice where a thick layer of unmelted powder sits above the mould surface to a thin lean mould where there is insufficient powder to provide the insulative cover which starves the liquid flux layer compromising the mould lubrication leading to potential defects and breakout. Manual addition can also lead to disturbance in meniscus and depending upon the type of mould level sensor used can cause disturbance in the automatic level control.

The next stage in powder feed development can be a constant feed mechanism which can be altered manually when required by the process. This still relies on the experience and attention of an operator. Simple automatic powder feed consists of a pipe suspended over the mould which discharges powder by gravity until the exit port is covered by powder built up on the surface. This is crude and tends to result in a very thick powder cover.

A more controlled method has been used which involves control of application based on a model or equation taken from previous plant data. Feed rate is then set using casting parameters.

The ideal for consistent and reliable feed is closed loop control. A number of systems are available with closed loop control including radiological, optical or laser-based measuring systems for mould powder thickness measurement ([172][173][174])

During the [EU-62.] (LUBRIMOULD) project, the ways in which the mould powder addition can affect the lubrication conditions were investigated. Trials showed variation in both thermocouple and mould friction as a consequence of the mould powder addition. Both these signals are affected by the addition of the powder. The friction, in particular, shows a sudden drop after the addition that is due to the return to the optimal lubrication conditions. Sudden changes of mould friction signals can be linked with lubrication problems and subsequent product defects. The increases in the friction and variation of this signal indicate that infiltration of the casting powder may be affected, decreasing the heat flux in the meniscus area. It was shown that for correct lubrication and infiltration of casting powder it is important to avoid the formation of large slag rims which can close the opening between the steel and the mould, preventing flow of liquid flux, and inhibit lubrication possibly leading to a sticker breakout. A new mould powder addition technique was proposed based on small and successive additions of mould powder to reduce the build-up of large slag rims.

Plant trials on a slab caster showed asymmetric mould powder feeding could cause mould powder break up which was significantly improved using automatic powder feeders and granulated mould powder. [EU-63.] (*TRANSIENT)* Permanent installation of mould powder feeders and use of granulated mould powder resulted in an 8% reduction in mould powder consumption.

3.4.4 Discussion and latest development

Mould powders are essential to crack free casting and there have been a number of projects dedicated in whole or part to the study of mould powder behaviour.

Almost every project has included a benchmarking element where data is gathered from commercial casters including monitoring and sampling of powders in use. This data is essential for the generation and validation of simulations.

Techniques have been devised to provide data including consumption measurement, slag sampling and retrieval of slag rim samples. A number of techniques for measuring thickness of layers have been used and one project compared the performance of these which involved dip tests using a variety of plates and wires to quantify the layer thicknesses. Best practice was established that the most reliable test results seemed to be obtained using plate dips with a plate of approximately 0.35mm thick, however, the results of these are still open to individual interpretation. [EU-57.]

Every project developed a database of powder and plant performance data. These tend to be project specific and there could be some benefit from compiling these separate resources into a unified data source. This would require centralised coordination to ensure objectivity and independence.

The composition of a mould powder can alter during casting particularly the alumina content as alumina inclusions are absorbed by the liquid flux.

Selecting a mould powder is a complex issue in that it is a compromise between heat transfer, lubrication and increasingly cost. The tools developed in these projects help with the selection process. For example, the thermal resistance of the flux layers increases due to two main factors: thickness and the crystalline fraction. Standard practice in steel plants is to use the basicity index to quantify potential crystal fraction however one project has studied this and suggested that Depolymerisation Index (NBO/T) is a better parameter for evaluation of the flux behaviour. Basicity index is commonly used because this is generally quoted on mould powder datasheets whereas NBO/T requires relatively complex calculation based upon powder formulation.

New and more powerful tools for powder selection have developed using numerical and computational modelling. Over time, as would be expected with developing digital technologies and techniques this has become more complex. Currently all the mould powder models are off-line models because mould powder optimisation is not something that needs to be done dynamically during operation. These models can be used in the specification of fluxes for specific plants and grades or to ascertain whether a standard commercial powder is suitable for a particular application.

A list of all the mould powder models generated during European projects can be seen in Appendix B. Models developed have included:

- Prediction of flux properties from powder composition including crystallisation and melting temperatures
- Evolution of the slag composition due to contact with liquid steel which potentially will lead to a change in flux properties
- Formation of liquid flux layers
- Flux layer thickness
- Flux flow in moulds
- Flux consumption
- Heat transfer through different flux layers
- Liquid fraction in the mould
- Stresses in the solidified shell and crack formation

These projects have demonstrated that modelling can be used to experiment with new conditions in terms of modification of the casting parameters and powders.

Heat transfer through the slag film which can be linked with solidification models to provide a complete solution from liquid steel through to mould cooling water. The most complex models are where different elements and separate models are being linked to create an overall simulation of the process including not just the mould flux but the entire steel solidification process. For example the model produced in the LUBRIMOULD project where the output of the CSM layer thickness model which creates a simulation of shell formation and heat transfer feeds into the model created by KIMAB which calculates the heat flux between mould and shell and thickness of the different layers in the gap as a function of the thermo/physical properties of steel leading to simulation of shell formation and heat transfer in the mould. This allowed estimation of the thickness of the shell at the exit of the mould and visualisation of flow pattern in melt and mould slag.

A number of physical models have been used in projects ranging from a full-size water model which simulates the whole system to a model using silicon oil to simulate liquid flux and moving belt to simulate the moving strand.

Powder consumption is a balance between the consumption rate and melting rate. The melting rate of a powder must be sufficient to maintain a liquid slag depth greater than the oscillation stroke length. The melting rate controls the liquid slag depth.

Mould powder feeding and consumption trials have been carried out investigate distribution of consumption across the mould. Consumption rate increases as the viscosity and break temperature of the flux decreases. For consistent mould powder performance particularly at high casting speed stable operation is essential, consumption increases when there is variation.

Feed mechanisms include manual, constant feed, gravity-controlled, simple automation based on calculated need, closed loop control which can be based on electromagnetic, radiological, optical or laser-based powder thickness measurement. Best practice consistency of application either by applying the powder 'little and often' or automated continuous feed.

Flux entrapment occurs when the horizontal velocity of steel at meniscus is high. There tends to be a threshold value below which it does not occur, but it is more likely to be caused by local velocity variations than a steady state condition. The first heat of a sequence is more prone to slag entrapment occurrence as this goes through a non-steady period and mould powder has yet to reach stable conditions in terms of lubrication. Entrapment can also be found when the mould level changes, periods of unstable mould level have been shown to correlate with coil defects. Entrapment increases with high superheat for carbon steels. Entrapment can also increase when velocity in the steel increases due to a restriction in the SEN outlet ports when clogging occurs.

Research into novel powders to overcome specific issues has increased with a significant effort going into carbon and fluorine-free powders. Significant research is ongoing worldwide especially by the powder producers.

Recently some work has been initiated which looks at novel approaches to mould power issues such as the INNOSOLID project looking at physical modification of the mould to use standard powders in a novel manner locally without interfering with their normal performance overall. There are ongoing projects such as NNEWFLUX which aims to develop a new type of mould powder which capitalises on novel liquid /viscosity properties to overcome limitations of conventional powders. Others such as OPTILOCALHT and RealTimeCastSupport are looking at innovative research ongoing worldwide into techniques to control heat flux etc. in conjunction with standard powders. These include an intumescent mould coating which forms a layer including controlled porosity and a process where an increased number of iron particles are incorporated into the flux to reduce heat transfer without changing the flux composition.

Potential for future work

- Creation of a unified database for mould powders

- Project to compare and contrast techniques used in modelling and suggest a method for the production of a unified comprehensive model to predict mould powder properties, how mould flux evolves during casting and interaction with the casting process.

- Techniques developed for local control of heat flux at the meniscus developed during the INNOSOLID project have potential for future development. Mould surface profiling did not progress to plant trials although it showed potential in pilot trials. It is also worth considering more practical experimentation with the concept of uneven water cooling in the top of the mould targeted to equalise heat flux even in the corners.

3.5 Process control & sensoring (BFI)

The process control & sensoring topic is related to the evolution of measuring instrumentation and control system tools and how they acted in increasing the performance of continuous casting process in term of safety, energy and raw material savings, reduction of defect occurrence on the final product.

The constant request of new steel grades with improved properties and higher quality demands on current and future steel production cannot ignore the exploitation of new measurement techniques, enhanced data processing techniques and numerical modelling for industrial plants to optimize thermal process control:

- Steel melt temperature measurements in-line in the mould,
- Enhanced data processing based on Big Data technologies to really exploit various and heterogeneous existing and new data from ladles down to quality supervision in real-time,
- Numerical modelling coupled with real industrial casting data to understand disadvantageous casting conditions and derive countermeasures,
- Continuous observation of the mould powder surface and derivation of its influence on melt temperature as well as lubrication and with it on surface quality,
- Development of new mould powders and thermal barrier coatings for the mould walls basing on improved understanding of their influence on the thermal conditions,
- Removal of Fluoride and Carbon from mould powders to decrease risks for environment, health and maintenance respectively to better control the powder melting behaviour and the temperature control in the casting machine.

The analysis of European funded research concerning the occurrence of crack formation in continuous casting process proved that measuring techniques and the development of control system tools play a strategic role: in fact, all the countermeasures that can be identified to optimize the process assume a suitable and reliable system to acquire useful data. The main output is the optimization of casting conditions, powder consumption and steel quality.

In the D2.2, the topic Process control & sensoring was divided into two subtopics: measuring systems and online control systems. The same division is reported in the present document to better analyse the influence of that topic on the understanding of crack formation in continuous casting.

3.5.1 Sub-Topic: Measuring systems

It is described the innovative instrumentation that directly measure the casting parameters and other process variables that are related to surface and internal quality of the final product. The most studied and developed sensor systems are related to Fibre-Optical-Temperature-Sensors (FOTS). The sensors with this technology found many applications and have been severely applied during the progress of various RFCS project. Of course, the data that have been collected have had various applications. In [EU-

71.] (*MASTERBILLET*), two FOT sensor equipment tracked the thermal field at top of the mould and the mould steel level and powder layer thickness. Successful plant trials highlighted the effects of manual powder feeding and meniscus level oscillation on the mould wall temperature. Continuous online information on gap lubrication and rim formation was reachable for the first time in long product casting.

This system was further developed to identify irregular casting conditions with particular reference to mould powder feeding, slag rim formation and irregularities in initial solidification. [EU-72.] (*FOMTM*) Forty temperature measurement positions were spread onto four faces of each mould. Two moulds were equipped and about 340 heats are measured. No significant indications of wear caused on the harsh environment at the caster could be observed, neither after the revamping procedure. Project aim was the development and operation of a better control of initial solidification at meniscus level to enhance the surface quality of as-cast products. The pilot installation of the novel measuring technique using FOTS has demonstrated that this technology can survive under the harsh environment conditions of a caster. With the chosen layout and corresponding handling, it was possible to withstand the revamping procedure while the FOT Sensor was inserted in the mould. The FOTS-system gives the opportunity of analysing events that happen inside the mould and were not able to be analysed before the installation of this technology. Relationship between events and the surface quality of the products has been observed, which has helped to determine new solutions to improve the process control and the strand quality. Strategies for optimized casting powder addition and corrective actions for assurance of a better quality of as- cast products were derived.

FOT sensor have been successfully used to monitor the mould wall temperature with indications of the current thermal profile, the position of the meniscus level and the influence of electromagnetic fields like stirring systems or brakes [EU-68.] (*INNOSOLID*). This system shows a higher resolution in space and time. Additionally, less space is necessary in comparison to thermocouples. A thick slab mould was equipped with two sensor rows including 10 measuring positions each. In the meniscus area the distances between measuring positions were lowered, so the operator of the casting machine was enabled to monitor the meniscus more precisely based on the temperature results. Physical and numerical modelling measures were derived and tested in operational trials. Operators are enabled to react on malfunctions at an early stage also by generated alarm values. The benefits were:

- More detailed measurement of heat dissipation in the meniscus area.
- More sensitivity of early identification of troubles based on strand shell growth.
- Improved monitoring and optimization of the casting process
- Reusable design offers the advantage to use for several mould plates or to avoid damage during revamping

FOTS measurement system was also successfully implemented in the narrow face of a slab caster [EU-68.] (*INNOSOLID)*. Modification of the cooling circuit led to the expected change in heat removal but did not affect product quality clearly. The application of grooves to the copper mould walls was found to be a promising approach. The aim of the project was to adjust the heat removal inside the mould

M-EMS was taken into account and numerical modelling was performed inside the project [EU-78.] . The work of this project aimed at the improvement of surface and sub-surface quality of as-cast billets and improvement of the process route. Main requirements of the casting mould are to produce a solidifying shell that is of adequate and uniform thickness and is free from surface defects, such as corner cracks and longitudinal cracking. For many years numerous casting plants which have the traditional mould thermal monitoring systems have developed algorithms to detect the onset of surface defects, such as longitudinal cracking. These developed systems generally have had only limited success, because of the very localised nature and initial small size (a few millimetres in length) of most surface defects. Even though thermocouples have been installed in mould walls of billet caster to measure and analyse thermal profiles in some studies [EU-65.] (*DIRECT DEFECT TOOLBOX-DDT)*, operational problems have appeared (the signal quality affected by M-EMS, water leakages arisen from huge amount of cables that need to exit from mould cassette, complex manipulation). In addition, thermocouples have to be uninstalled from the mould before revamping it. Thus, it is necessary to install thermocouples again once the mould is revamped. Due to the necessity of using an individual cable for each thermocouple, the amount of measurement points has to be limited because of the lack of space in the mould. Thereby the capabilities of the breakout system are limited.

These disadvantages have shown the necessity of developing an innovative technology that avoids those difficulties. However, even though there have been many efforts to develop monitoring systems that could help to identify abnormal situations inside the mould for long product casters, there is still a long way to go in terms of feasibility, reliability and process robustness. The reasons for abnormal situations are numerous and can be put into several categories, namely sticking in the mould, longitudinal corner or off corner cracking, mould hangers/finings and other related mould issues, start of cast, arrested teem failure following a stop period (including a flying tundish change, non-metallic entrapment, mechanical consideration (mould oscillation) and miscellaneous (loss of stopper control, loss of auto-level control). In many instances key process measurements, such as mould temperature measurements and the related thermal contour maps are not available. The conditions of the continuous casting machine strongly influence the slab quality like surface defects or internal cracking. The segment rolls should be aligned exactly to the desired positions before the beginning of casting. Therefore, a Caster Strand Monitoring System (CSM) was developed by Lee et al. [80]. The CSM is designed to measure the roll gap, roll bending, roll alignment, roll rotation and the strength of the water/mist spray for slab cooling. A mathematical model for the position control and alignment of the continuous casting machine equipment was developed by Sholomitskii et al. [81] based on high-precision geodetic measurements.

3.5.2 Sub-topic Online Control systems

The online control systems are addressed to the improvement of caster and process stability, in order to reduce cracking. It includes control of mould level, process parameter and secondary cooling pattern.

The various control systems adopted in RFCS project and other scientific literature have been developed to manage one or more specific aspects of the process, according to the influence of the process parameters to the occurrence of crack formation.

In the frame of crack formation, it has been found that the transient conditions are particularly critical in term of defects formation. Studies have been done in project [EU-70.] (*TRANSIENT*). The project is aimed at understanding the causes and effects of transient conditions on surface and internal quality. Different measurement systems were developed, e.g. a mould powder coverage monitor. It was found that insufficient mould powder coverage has a tremendous influence on the strand surface quality. Transient conditions included casting speed variations, flow rate changes, ladle changes, flying tundish changes, start and end of casts, and grade changes. Innovative caster monitoring systems and advanced models using CFD, FEM and finite difference methods, as well as artificial neural networks were developed. Plant trials on five industrial casters covering a variety of formats and grades led to the identification of a set of transient phenomena. This has allowed for the development of new operational practices to eliminate or reduce quality problems associated with transient events and of new rules for downgrading as-cast material following transient events.

Breitfeld [EU-69.] (*Advanced methods for an improved mould heat transfer control)* utilised experimental, analytical and numerical tools in order to conduct research on cooling systems in slab casting moulds. Transient thermocouple readings, mould powder properties, phase transformation during solidification, surface quality, friction forces, local and global heat withdrawal from slabs and billets were correlated with process conditions. It was concluded that mould heat flux cannot be applied for process control itself but is an excellent mean for off- and online process observation. there are still some parameters that are difficult to assess and control, such as the complete thermal profiles of the four faces of the mould. This information could bring a very important advantage in terms of identifying risky situations as, for example, a non-homogeneous growing of the solid shell. There are some devices and technologies that have been developed to analyse thermal profiles inside the casting mould. A widespread one is the installation of a large amount of thermocouples along the whole mould walls, that is, mould thermal monitoring systems, [64]. Presoly et al. [66] assumed a considerable effect of initial solidification on surface quality and casting productivity. Therefore, they installed an online thermal monitoring system. It was found that the quality of the strand surface decreases with increasing temperature fluctuations in the mould.

Secondary cooling control was not covered in deep european research projects. Popular control models for secondary cooling their principles and characteristics were reviewed by Dou et al. [68]. Based on this review a new control model was developed combining the advantages of the available models and estimating temperature profile and crater end position. Current problems with secondary cooling control and the related development trends were discussed.

Fluctuations of position of the metal level in the mould disrupts solidification, entrains slag and leads to many quality problems. The liquid level is usually measured with a commercial system using a suspended eddy-current level sensor or a radiation detector. Optimised sensors for mould powder thickness and mould level are presented in [48], [49], [50]. Another potential method to quantify the metal level during continuous casting is to utilize the temperature measured continuously by thermocouples embedded in the copper mould [62].

The application of a liquid metal model was used to produce a set of novel tools to predict the formation of defects. Microstructural evolution of cracks was observed. [EU-65.] Developed numerical models predicted the microstructural evolution of the shell. Direct defect prediction was possible through numerous plant trials and liquid metal experiments to characterise the heat transfer and dynamic behaviour of the slag-bed and meniscus (particularly, at the meniscus corner where initial solidification occurs). Microstructural evolution including the formation of defects (cracks) was observed through novel in-situ experiments and steel properties were addressed through high-temperature measurements. Numerical models that predict metal-slag-argon flows, heat transfer, mould oscillation, solidification, stress-strain, shell microstructural evolution and the explicit formation of defects were developed in order to provide the steelmakers with a new set of tools to improve the casting practice.

Various control systems have been developed with the aim to improve safety conditions during continuous casting. In [EU-66.] (*DEFREE*), critical parameters affecting steel quality have been analysed and safety ranges to ensure good quality in continuous casting have been found. Several fundamental and semi-empirical models were developed and used for process simulation in the project. Cracking indices, fluid flow parameters in the mould and segregation severity parameters are examples of critical parameters defined in the project. Safety ranges inside which the critical parameters had to stay during casting were determined for steady-state casting conditions.

3.5.3 Discussion and last developments

Hard spots are local areas with increased hardness on the surface of semi-finished or end products in steel manufacturing. As the incident rate of hard spots is extremely low, only a 100% inspection of production can ascertain their detection. Schneibel et al.[55] presented an eddy current based inspection. Current data and results from in-production inspection show the capabilities of the new technique. An outlook towards a 100% inspection system is given.

In the project EDDYCAST [EU-73.] a methodology for crack detection was developed. It was successful in several plants for billets, but for crack detection at continuously cast slabs at Dillinger the proposed and tested method did not work properly since

a) The slab temperature at exit of caster was in a critical range for a good in-line eddy current measurement application (i.e. around Curie temperature). In slab yard at lower slab temperatures the system worked better.

b) The cracks in the investigated area of the slab corners were mainly closed at the slab surface due to rolling forces in the caster (soft reduction and driving rolls). This caused a bridging of steel that enabled "normal" eddy current flow, i.e. the cracks could not be detected.

The project NDTCASTING [EU-76.] has shown the possibility of the EMAT system on hot surfaces with oscillation marks and scale. The project demonstrated that sensitive flaw detection under these difficult conditions is possible - defects with a length less than 10% of the chosen wavelength (λ = 14.9 mm) can be repeatedly detected.

- EMAT-EMAT – A prototype was developed capable of detecting surface and subsurface defects on-line at high temperatures (below the Curie temperature of steel).
- Laser – EMAT - A prototype Laser-EMAT system has been developed. The system has been proved in the laboratory on cold samples. Hot trials have been of limited success with surface defects being detected in some samples.
- Conoscopic holography – The existing plant system has extended for detecting other defects in addition to the longitudinal crack already in operation such as very thin and zigzag cracks can now be reliably detected. Overdetection has been decreased.

In the project NDTSLAB [EU-74.] the EMAT system has been demonstrated to be capable of finding defects in as-cast steel slabs that cannot be found visually with grinding or scarfing of the surface.

With tuning of the signal to noise ratio in the surface scan image defects as small as 5 mm^2 can be detected. Defects smaller than this are not readily detected by the EMAT system.

Hooli [52] developed a system for the visual inspection of hot slabs during casting (Reveal CAST) which is able to define the surface quality of slabs.

Fibre optical temperature sensors (FOTS) have shown their potential during applications in the previous years [44], [58], [57], [59], [60]. FOTS systems are characterised by a very short response time and are not influenced by electromagnetic systems. These advantages provide the potential for application in moulds with EMS.

Today modern temperature measurements with short response times enable the control of EMS systems. Feldmeyer et al. [EU-72.] (*FOMTM)* introduced a FOTS fibre optical measurement system successfully to a billet caster system. This technique is basically able to control the casting process in real-time due to the very quick response time.

The work of Stamp et al. [EU-79.] (*CONSOLCAST*) includes comprehensive monitoring of solidification. Ramirez Lopez et al. [EU-80.] (*SUPPORT-CAST*) take into account novel online-monitoring and advanced modelling aiming at adjusted process control. Real-time measurement of shell-thickness aims at product improvement in the work of Barbero et al. [EU-81.] .

Excessive meniscus steel level fluctuations were suspected to be one of the sources for exogenous non-metallic inclusions, as well as possible source of surface defects. Rohac et al. [56] successfully suppressed the influence of Stir Systems on electromagnetic mould level measurement systems (MLM System) in two steelworks.

Temperature control plays a major role in the continuous casting process (CC). Especially the avoidance of surface cracking for different steel qualities and different slab sizes needs optimisation of the thermal control. However, the internal thermal and flow state within the mould, in particular in the crucial area of solidification below the meniscus, is extremely complex. Considering the interacting influences of melt temperature and flow, solidification, cooling and mould powder main parts of the internal processes are still not understood despite a large number of research projects covering several decades.

This is still an issue in industrial operation since the melt temperatures fluctuate significantly due to the discontinuous processes in the steel shop. The melt temperatures supplied from ladles and tundish frequently change due to varying melt levels, holding times or ladle changes. The research and development effort in the last decades achieved a large degree of monitoring and control of CC plants, but unfortunately just the conditions in the crucial area around the meniscus cannot be directly measured, yet, but have to be roughly estimated from single temperature measurements in the mould copper. Furthermore, it is hardly possible for the operational staff to assess even the limited existing data since the results from quality supervision are only provided hours or days later, and in a format (e.g. spatial measurements) which is difficult to combine with other measurements.

As consequence, the relevant thermal conditions in the mould and their influences on surface quality are still highly non-transparent and automatic control of this important part of the process is still clearly limited. While many crucial aspects of the continuous casting process are not yet understood and are non-transparent, the corresponding control actions have to be done manually by experience. Steel industry needs to go towards Industry 4.0. There is urgent pressure to strongly improve the levels of knowledge, digitalisation and control.

In the following some examples are given for the most promising and useful emerging development lines and future trends concerning measurement techniques:

Atzlesberger et al. [53] and Kareem et al [54] described a system for continuous temperature measurement in the tundish basing on the thermoelectric effect (also called Seebeck effect).

Lamp el al. [42] developed the measurement system DynTemp®. An optical fibre was continuously fed into the melt of an LD converter and yields continuous monitoring of the melt temperature. Kordel et al. [43] applied this approach also successfully to a ladle furnace. The innovative technique has proven to give valuable information on liquid steel temperature evolution.

Up to now the DynTemp® based liquid steel temperature measurement was applied to a converter, an EAF and ladle furnace. Here possible slag entrainment caused by the moving fibre does not degrade the melt quality at this early stage. The application of this innovative technology to the mould, where entrainment of liquid mould powder has a huge influence on melt cleanliness, will provide very precise temperature information of the steel melt. But the careful introduction of the fibre into the melt through a refractory tube supported by an inert gas like Argon is a big challenge. This will be done for the first time in the running project RealTimeCastSupport [EU-81.] .

Influence of transient effects like a ladle change on thermal evolution can be analysed in detail.

Three different measurement techniques will be applied and utilised in parallel in the running project

- (1) IR-based monitoring at the casting powder surface,
- (2) local temperature measurements in the copper mould plates with thermocouples and with FOTS,
- (3) DynTemp® based liquid steel temperature measurement in the tundish and in the mould.

Additionally, FOTS will be applied to a mould equipped with a multi-mode EMS. Quick response of the FOTS system enables the control of melt temperature and flow indirectly with the multi-mode EMS.

In the running RFCS-project SHELLTHICK [EU-81.] a solidification process optimisation tool providing the operators with real-time information on the billet solidification process as cross-section shell thickness is developed. Additionally, the tool provides the operators with real-time information about surface defects (bulging, depressions & rhomboidity) on the billet and (based on the output of the previous tools) would allow the operators and/or managers to define the optimal continuous casting process parameters to improve quality (minimising the generation of surface defects) and productivity.

Weidermann et al. [76] developed a new technology for flow measurement in liquid steel to determine the time-dependent liquid flow through a submerged entry nozzle (SEN). The measurement system reaches a resolution of 0.5 kg/s with a response time of 100 ms for a 2.5 kg/s mass flow jump. The device performance has been evaluated under laboratory conditions. A first operational trial in a steel plant has been done.

Contactless inductive flow tomography (CIFT) was implemented at several physical models of slab casting moulds by Ratajczak et al. [77].

As a conclusion, these innovative measuring techniques should be further developed in the future:

- Continuous temperature measurement in the tundish
- Control of melt flows
- Monitoring of mould powder layer
- Measuring of temperature in mould copper walls
- Monitoring of spray cooling
- Measuring the temperature of the strand surface
- Detection of cracks

4 Overview of the analysis (in view of the roadmap)

The occurrence of defects during continuous casting process can be induced by several parameters that have to be considered all together, since they are influenceable each other. Many efforts have been done during these years in order to better understand the correlation of defects and process parameters: in that frame the development of reliable models, quality prediction systems and sensoring & monitoring tools play a strategic role.

As general view, the RFCS research led to actual important results, in term of basic knowledge of physical and chemical phenomena inside the steel, definition of possible countermeasures to reduce the incidence of one or more defects, the development of new powder concept, set-up and application of digital tools to control the process and/or monitor the plant events.

The progress of every EU project contributed to enhance the quantity and quality of basic knowledge, highlighting hidden mechanisms of defects formation and consolidating acquired competences. Segregation of sensible elements have been faced in deep, in particular the role of Boron, due to high importance that is addressed to the production of micro-alloyed steel grades: the future work should be aimed to assess the role of other elements in Boron interdendritic segregation. Another problem that it is faced was about the role of induced strains during secondary cooling: the amount of strains still is difficult to calculate but it plays a crucial role in intergranular crack formation.

The progress of basic knowledge in cracks occurrence in CC allows to adopt a series of countermeasures that allow to improve casting conditions. Every EU project reports a detailed series of operations that promote the improvement of final product quality. Despite the important results achieved, it is quite impossible to define a specific recipe for different steel grades and different types of defects. Every attempt of improvement should be calibrated based on plant layout, production needs, raw material and level of plant digitalization. For this reason, the present document can be seen as a list of well-working solutions, a sort of start point for further optimization pathways.

Since the specific role of powder in the management of casting process and the attention dedicated to this topic in many EU projects, it was stated to treat that aspect differently from other process parameters: innovative solutions have been proposed and tested, reaching high values of TRL; however, it emerges the necessity to create a unified mould powder database, in order to avoid a lack of information. There are already ongoing projects to further develop concepts in control of heat transfer at the meniscus and in the mould by the use of intumescent coatings and iron particles in the flux layer. [OPTILOCALHT and RealTimeCastSupport]. The development of non-Newtonian mould flux is also already being investigated in the NNEWFLUX project.

The optimization of the process (and also powder mould properties) is strictly related to the development of numerical/mathematical models as well as the disposal of effective tools to collect, monitor and process data. The development of numerical/mathematical models has been faced during most of EU projects, achieving also high TRL (ex. Prediction and validation models can be considered as TRL 5). However, many times, an incomplete economic assessment and lack of application cases limited the implementation of such a model. Applicability and industrial implementation are undermined by the lack of guidelines set.

The disposal of reliable methods to collect and process data is fundamental since it allows to have useful data to "feed" every developed model or to predict the behaviour of the process. In this field, the use of Fiber-Optical Sensors (FOTS), in-line steel melt temperature measurement in the mould represent the most studied technologies, with a TRL 6/7. Online control systems are also strongly studied in EU projects, but the influence of all parameters is still not understood. In this contest, barriers remain for continuous observation of mould powder surfaces and continuous temperature recording in tundish and mould, due to the limited accessibility conditions. Systems for the detection of cracks are developed with the use of eddy current measurements: EMAT system has been proved to be able to find defects is as-cast steel slabs. In the future, it is reasonable to improve the system in order to catch defects smaller than 5 mm^2.

The table 4-1 in the next pages summarises the main points of discussion.

As a general comment, the realistic TRL steps forward and the consequent impact on the production and quality in the future cannot be disconnected from the economical/financial and regulation scenario to drive the steelmakers strategy. This will be matter of the roadmap that will be set up as final project outcome and that will take benefit from the information collected directly from the stakeholders along with the events and the related consultations actions.

Table 4-1:Overall assessment of each topics

Topic	TRL level	Main barriers	Overall comments
1. Basic Knowledge	Limit the boron interdendritic segregation	The potential of other chemical elements to control the B interdendritic segregation by forming a boron compound is being investigated.	Boron accumulates in the interdendritic liquid, reducing its solidification temperature down to 1150 ºC with formation of Fe_2B. Such a low melting liquid enhances segregation cracking
	Explain if intergranular cracks (IGC) could be due to surface strains during secondary cooling	Surface strains during secondary cooling are difficult to calculate as the accumulation of strain since	Formation of IGC is frequently related to semis straightening strains. However, surface strain can be developed during

		the beginning of solidification should be considered. But high temperature behaviour of the material is unknown and is difficult to measure with laboratory tests	intensive secondary cooling due to nozzle mal-functioning.
	Control of semis surface Austenite Grain Size (AGS) during casting with temperature cycling.	To identify the steel grades, which can undergo temperature cycling without the formation of cracks during the temperature cycling itself.	AGS influences IGC and surface transversal cracking. Temperature cycling has been tested for controlling AGS. Not introduced to industrial scale, due to contradictory results depending on steel composition.
	Establish the billet tertiary cooling rate to avoid transformation cracking of microalloyed steels	New matter of research in the CC due to new steel grades containing several microalloyed elements and high cooling rates at the tertiary cooling due to high production rates.	Internal/surface tertiary cracking is depending on composition, microalloyed content and billet cooling.
2. Modelling	Based on the analysis presented, the TRL of European Funded Projects is quite wide going from model setup and development which would be equivalent to TRL 1-2, passing through calibration (TRL3), Predictions (TRL4) and Validation (TRL5). However, the final implementation in the plants is often missing or there is no clear evidence if the models developed are in use after the project. and development	The main barriers for further implementation of the models are: - Incomplete validation of models - Lack of application cases - Lack of quality data to compare with results - Incomplete post-project economic assessment to identify yield and/or resource savings achieved thanks to modelling.	Results show that modelling efforts in EU projects are substantial. However, an extended assessment of their impact is necessary or a new set of guidelines when projects are applied is required to ensure their applicability and final industrial implementation. This can be done by the Commission by means of questionnaires, 6 months or 1 year after project end. Looking for evidence of follow up projects or

		- Models too complex (require highly-skilled staff) or too CPU-time consuming to be applied by the industry	assessment in dissemination actions such as VALCRA. One path to full exploitation of complex model tools for continuous casting at the industrial level is the *replication technique*, consisting in developing an easy to use and CPU-cheap model which can reproduce the results of complex physical models in industrial environment and is intended to be used by staff without specific knowledge in modelling
3. Process Optimization	There is not a specific recipe to optimize the continuous casting process. During the years, several efforts have been made to deeply understand the interaction among steel composition, casting parameters and occurrence of defects. The increased awareness of microstructure evolution inside the steel leads to definition of key-elements whose composition should be considerered in terms of defects occurrence. Cooling strategy can be optimized based on outputs of models and measuring systems in order to avoid that temperature falls in ductility drop ranges in	Large amount of variability of the continuous casting process. The best operating window needs a preliminary study for specific product and steel grade. Implementation of new caster layout often involves the necessity of large investment that not always can be sustained by steel companies Improved chemical composition could be the preferential route to minimize certain type of defects but the risk is not to achieve the target mechanical properties of	Process optimization involves many sub-topics inside the continuous casting process. The use of mathematical models is fundamental to explore various innovative solutions. They need to be reliable and characteristic of the problem that is intended to solve The exploration of various solutions is related with reliable methods of measurement in order to have meaningful/reproducible results.

	critical areas/phases of the process. Secondary cooling is more influent in casting of billets than slabs. The constant attempt to improve the CC process thanks to the more focused studies leads to a general increase of product quality. Experimental trials performed during the progress of RFCS projects proved the possibility to improve quality, reducing costs and increasing productivity. As reported in D2.2, the overall achieved TRL of proposed solutions is 6-7.	final product and the acceptability range Experimental campaign is always required	
4. Mould Powders	Unified mould powder database	Large amount of data held in significantly different formats by many companies and research organisations	Would require centralised coordination to ensure objectivity and independence
	Unified comprehensive mould powder model.	Many models have been created of varying degrees of complexity. Compatibility between models and degree of interaction with casting models.	A unified model to predict mould flux properties, evolution and behaviour during casting
	Carrying on from the INNOSOLID project - local control of heat flux at the meniscus. -LDCC targeted mould cooling -SCPC Mould surface profiling TRL 7	LDCC involves modification of cooling channels etc. in a casting mould. For plant application would require design, manufacture and installation of custom mould plates. SCPC. Further pilot studies are required to confirm the	The two different concepts would Two different things. Targeted cooling requires more practical experimentation with the concept of uneven water cooling in the top of the mould. Surface profiling did not progress to plant trials

		benefits of mould plate profiling before a production plant would agree to plant trials.	although it showed potential in pilot trials.
5. Process control and sensoring	Steel melt temperature measurements in-line in the mould Thermocouples Fibre-Optical-Temperature-Sensors (FOTS) TRL 6/7	Signal quality of thermocouples affected by M-EMS; water leakages arise from huge amount of cables that need to exit from mould cassette; complex manipulation; thermocouples have to be uninstalled from the mould before revamping it. Due to the necessity of using an individual cable for each thermocouple, the amount of measurement points has to be limited because of the lack of space in the mould.	The pilot installation of the novel measuring technique using FOTS has demonstrated that this technology can survive under the harsh environment conditions of a caster. FOTS shows a higher resolution in space and time, needs less space in comparison to thermocouples. Continuous online information on gap lubrication and rim formation was reachable for the first time in long product casting
	Continuous observation of the mould powder surface TRL 6	Harsh conditions, limited accessibility	It was found that insufficient mould powder coverage has a tremendous influence on the strand surface quality
	Online control systems TRL 6	Considering the interacting influences of melt temperature and flow, solidification, cooling and mould powder main parts of the internal processes are still not understood.	Even though there have been many efforts to develop monitoring systems that could help to identify abnormal situations inside the mould for long product casters, there is still a long way to go in terms of feasibility, reliability and process robustness
	Continuous temperature measurement in the tundish and in the mould TRL 5	Limited accessibility. The careful introduction of the fibre into the melt through a refractory tube supported by an inert gas like Argon is a big challenge.	Up to now the DynTemp® based liquid steel temperature measurement was applied to a converter, an EAF and a ladle furnace

	Detection of cracks TRL 5	Crack detection by eddy current measurement at continuously cast slabs does not work properly if the slab temperature at exit of caster is in a critical range (i.e. around Curie temperature). In slab yard at lower slab temperatures the system works better. If the cracks in the investigated area of the slab corners are closed at the slab surface due to rolling forces in the caster (soft reduction and driving rolls) the cracks cannot be detected. EMAT-EMAT – A prototype was developed capable of detecting surface and subsurface defects on-line at high temperatures (below the Curie temperature of steel) Laser – EMAT - A prototype Laser-EMAT system has been developed. The system has been proved in the laboratory on cold samples. Hot trials have been of limited success with surface defects being detected in some samples. Conoscopic holography – The existing plant system has extended for detecting other defects in addition to the longitudinal crack already in operation such as very thin and zigzag cracks can now be reliably detected. Overdetection has been decreased.	Success with eddy current measurement system in several plants for billets. But eddy current measurement system for 6-strand equipment would require capital expenses of over 2 M€, which provides insufficient payback. The EMAT system has been demonstrated to be capable of finding defects in as-cast steel slabs that cannot be found visually with grinding or scarfing of the surface. With tuning of the signal to noise ratio in the surface scan image defects as small as 5 mm^2 can be detected. Defects smaller than this are not readily detected by the EMAT system.

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6 APPENDIX A: Summary of computational and physical modelling performed in European funded projects over the last 20 years

Company	Project	Topic	Technique	Success	Comments
CSM	7210-PR/273	Predicting flux consumption.	Calculation based on viscosity and melting temperature	good agreement with measured values	
Corus	7210-PR/273	Predicting flux consumption	Calculation based on thermal and mechanical behaviour of flux and steel	Uncalibrated with plant data	
CSM	FLUXFLOW	Flux layer thickness and the flow conditions in moulds for long products	CFD numerical simulation	Correlated with plant data	
BFI	FLUXFLOW	Formation of liquid flux layer	Physical water model and CFD numerical simulation (FLUENT)	validated operational observations	
BFI	SLAGFILMOWL	In-mould conditions liquid fraction in the mould and stresses in the solidified shell and crack formation-special steel blooms. 3D	CFD numerical simulation. Finite Volume Method for the fluid-mechanical Finite Element Method for the thermo-mechanical	Good agreement with physical phenomena and to published literature	Could be expanded for other steel grades and casting conditions
CSM	SLAGFILMOWL	Evolution of the slag composition during	Thermodynamic calculation and ThermoCalc	Compared to mould powders and	

		solidification. Determination of crystallisation and melting temperatures		slags taken from industrial casters.	
KIMAB	SLAGFILMOWL	Heat transfer through the slag film	2D model, with COMSOL Multiphysics Finite Element Method	Validated by plant trials	Shell thickness model was not completed. Given continued supported by the Swedish government.
CSM	SLAGFILMOWL	Thermal model of heat transfer to calculate the thicknesses of the vitreous, crystalline and liquid layers and the different thermal conductivity values of each single layer of the slag film	Numerical and thermal model	Validated against plant data. Valid for different casting conditions and mould geometries.	
CSM	LUBRIMOULD	Physical model using scale model of the billet mould including oscillation, silicon oil to simulate liquid flux and moving belt to simulate the moving strand	Physical Simulation	Requires correlation with industrial casters	
TATA	LUBRIMOULD	Physical model using scale model of the	Physical Simulation	Requires correlation with	

		slab mould including oscillation, silicon oil to simulate liquid flux and moving belt to simulate the moving strand		industrial casters	
CSM	LUBRIMOULD	Calculating the heat flux between mould and shell and thickness of the different layers in the gap as a function of the thermo/physical properties of steel	Numerical model	Model can assess evolution of the liquid and solid slag layers for comparison to mould thermocouple data	
Kimab	LUBRIMOULD	Taking input from CSM layer thickness model simulation of shell formation and heat transfer. Estimation of the thickness of the shell at the exit of the mould. Visualisation of flow pattern in melt and mould slag	Thermo-fluid-dynamics using with COMSOL Multiphysics		
BFI	LUBRIMOULD	The fluid-flow and the dynamic behaviour at the meniscus formation of meniscus	Physical and numerical (FLUENT) modelling	Physical model was used to validate numerical results	

		interface perturbations and lack of liquid flux feeding			
BFI	FOMTM	Heat transfer model to evaluate different sensor positions with respect to the investigated boundary conditions	Numerical	Validated against operational practice	
Tata UK	INNOSOLID	Predict the development and change of the phases formed during solidification of the liquid flux	Factsage		Performed using standard commercially available software
VAS	INNOSOLID	Simulation of heat transfer and infiltration of proposed grooved copper surface profile	Finite element	Infiltration confirmed by laboratory simulation	Project specific

7 APPENDIX B: Links between cracking and casting conditions

There are many links between casting parameters (steel composition, mould powder, heat flux, mould level etc) and cracking in the casting process. Much of the information in this section has been referenced from what is described in the previous chapters and various reviews present in scientific literature. Much of information are covered in much greater detail in "The Casting Powders Book" by Kenneth C Mills and Carl-Âke Däcker. [1] and "A review of causes of surface defects in continuous casting" by F.R. Caminsani et al [2].

The present appendix has not the aim to provide a complete and detailed analysis of the entire world concerning continuous casting defect occurrence. It would be a short review of the main defects faced and studied in the analysed RFCS projects.

7.1 Longitudinal cracking

Longitudinal cracking occurs in two main types: gross and shallow subsurface cracks. Steels in the peritectic range are particularly susceptible, due to the peritectic transition (Fig. 1) which occurs on cooling causing significant shrinkage of the solidifying shell in a small range of temperature.

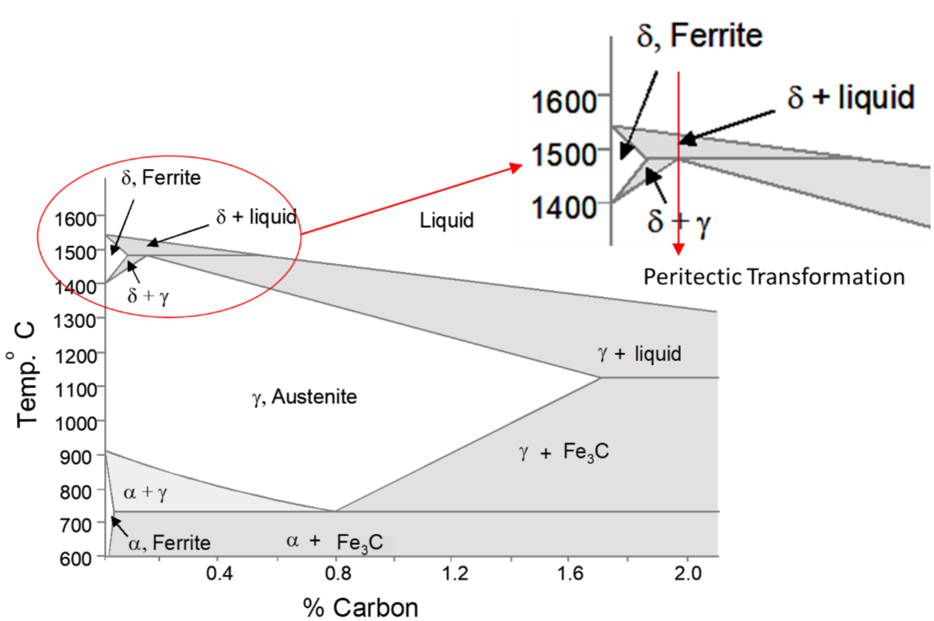

Figure 7-1:Iron-Carbon diagram showing Peritectic transformation point

The transition from ferrite a body cantered cubic structure to austenite a face centred cubic structure is associated with a volume shrinkage which generates stress in the solidifying shell leading to cracking.

To reduce the likelihood of cracking the effect of shrinkage needs to be minimised in the top region of the mould where the strand is most vulnerable i.e. thin and weak. The heat transfer in the vulnerable meniscus region where initial solidification is occurring must be reduced to minimise shell thickness and thus the stresses generated by shrinkage. This can be achieved by selection of mould powders that form a thick crystalline slag layer. The thick slag layer increases the thermal resistance which is enhanced further by the scattering effect of the crystalline content. It is critical that local variation in the slag layer be minimised to reduce localised stress.

Mould powders can further reduce heat transfer by the inclusion of metal oxides which absorb heat rather than transferring it.

Composition of steel plays also an important role in the formation of longitudinal cracks. The main cause is associated to detrimental segregation phenomena that have to be minimized. The occurrence of longitudinal cracks is influenced by the presence of sulphur mainly. The presence of other segregating elements is also detrimental: V, Nb, Al, in combination with carbon and nitrogen. The precipitation of these compounds leads to the formation of brittle phases: in connection with induced stresses (including thermal stress), there is the risk of cracks. The occurrence of these defects is more relevant for wide slabs.

It has been reported that the amount of cracking will significantly increase when the heat flux exceeds a critical level. The control measures in place must ensure that the flux remains below that. Other parameters that affect the occurrence of this defects are taper loss, irregular mould oscillation and mould worn.

Other techniques have been used to increase the slag layer and reduce heat flux such as localised reduction in water cooling and the application of grooves on the copper to increase slag thickness locally [2]. As reported in many RFCS projects, benefits have been achieved by adoption of appropriate mould powder and adoption of soft cooling technique.

7.2 Longitudinal corner cracking

Longitudinal corner cracking has a similar cause to longitudinal cracking in the face in that the uneven stresses in the shell caused by transition shrinkage leading to uneven shell thickness overcome the strength of the newly solidified shell causing it to crack. In the corners heat is extracted in 2 directions meaning that there is more cooling and shrinkage than in the centre of the mould. The initial overcooling leads to a thicker shell which can pull away from the mould creating an air gap which can significantly reduce heat transfer locally.

A second mechanism can then come into play where the subsequent lack of cooling in the corners leads to melting back of the shell due to circulation of liquid steel in the mould thinning the shell at a point just away from the corners. This can exhibit itself as a depression (or gutter) just off the corner where the thinner shell pulls away from the mould surface and bends inwards. Small cracks can be found in the root of the depression

To overcome this type of cracking a similar approach can be taken using a thick crystalline slag to reduce the heat flux to create a thinner more uniform shell which generates less stress and strain.

Other methods can include reducing cooling at the mould corners or rounding off the corners.

The control of mould taper is also fundamental to reduce the occurrence of this kind of defects.

Mould level is another parament to be considered: large mould level variations can lead to the formation of longitudinal corner cracks.

Thinning of the shell can be reduced by careful design of the flow patterns within the mould or reduction of the speed of flow using electromagnetic braking. In order to handle the heat flux inside the mould, particular care has to be addressed to gap formed by steel and mould face and possible entrapment of air that worsts the heat exchange, promoting the formation of expansions and retractions on steel surface.

7.3 Sticker Breakouts

Sticker breakouts occur when a loss of lubrication leads to a thinning of the solidified shell. The increased friction locally causes the surface of the strand to "stick" tearing the shell and allowing liquid steel from within to "breakout". Once liquid steel begins to flow it will expand the breach and potentially lead to a catastrophic failure to contain the liquid core terminating the cast and potentially causing significant damage and mess in the caster.

The loss of lubrication can be caused a disruption in the slag at or near the meniscus caused by islands of solid material that have formed from inclusions or unmelted powder that cause a discontinuity in the slag rim. Disruption of the slag rim can also occur when a rim breaks due to significant changes in the mould such as gross level changes or casting speed changes.

To reduce sticker breakouts there are thermocouple-based systems such as the MTM system available to detect breakout-risk susceptible temperature profiles and automatically take remedial action, slowing the strand to allow the thinning of the shell to "heal".

The selection of mould powder can be used to reduce the likelihood of sticker breakouts. A low crystallinity "glassy slag which has a relatively high heat transfer will promote shell growth and improve strand strength.

7.4 Oscillation Marks

Oscillation marks are transverse ripples in the shell surface caused by the upwards motion of the mould during oscillation. These depressions can be the cause of transverse cracks at the route of the oscillation mark where the solidifying shell is thin. The severity of cracking can depend upon the depth of the mark. Oscillation marks are affected by a great many factors discussed elsewhere. The relationship with mould flux is linked to powder/flux consumption and horizontal heat transfer.

The oscillation marks form in the first steps of steel solidification.

Powder consumption is led by the pumping action of the mould oscillation propelling liquid flux down the mould. Viscosity plays a part in this along with depth of mould oscillation marks. The greater the powder consumption rate the greater the depth of oscillation mark. Low viscosity flux also tends to be consumed faster.

The occurrence of oscillations marks is influenced also by casting speed and heat flux. High casting speed can be beneficial, while an increase of heat flux can be detrimental.

7.5 Transverse and Corner Cracking

Transverse and corner cracking occur usually through deformation during bending, straightening or incorrect mould taper. It can also arise from stress at the base of oscillation marks from local segregation. It occurs predominantly when fast or uneven cooling strategy is applied.

Sticking is also responsible of transverse cracks since it increases the friction of mould-strand interface. Friction can be induced by unsuitable mould taper, casting speed variations, mould oscillation and mould powder. Moreover, composition of steel can be another important parameter that affects the occurrence of these defects. The analysis of RFCS projects states that the presence of relevant segregation phenomena is attributable as the main cause of transverse cracks. In particular, Nb makes slabs more susceptible to transverse cracking. It implies the formation of brittle phases that promote the formation of crack when stresses are applied on the steel (during bending and unbending for example). Possible countermeasure is the control of secondary cooling strategy in order not to drop the ductility zone. In general, if the steel is susceptible of brittle phases precipitation, optimization of steel composition have to be taken into account. Boron is another element that strongly tend to segregate. Moreover, the segregation phenomena that can lead to possible transversal crack formation concern also phase transformation of steel crystalline structure. Transverse cracking phenomena can be also reduced by the use of an appropriate mould powder with a high break temperature promoting lower heat transfer through high crystallinity.

7.6 Star Cracking

Star cracking tends to occur low down in the mould during periods of fluctuating heat flux which can be linked to a lack of lubrication due to insufficient liquid flux or fracturing of the solid flux layer. The fluctuation causes local stresses in the solidifying shell which can lead to small cracks radiating in a star pattern.

The presence of star cracks is influenced by superheat and casting speed.

Poor mould powder and slag pool depth leads to poor heat transfer and lack of lubrication. A thick crystalline slag will reduce heat transfer increase shell thickness and produce a thicker liquid slag layer which will ensure that the mould is fully lubricated.

7.7 Conclusions

It is possible to state that the occurrence of defects is related to steel composition (segregation phenomena) and temperature strand. Composition of steel does not change dynamically during casting but it characterize the precipitation of possible compounds that produce brittle phases. It is related to temperature strand. Temperature in turn can be monitored by different factors. That makes the conduction of the process quite complex. Moreover, together with the process variables, other factors have to be considered such as safety conditions for the operators, productivity, correlation with other plant operation etc.

In Table 7-1, a summary of defect occurrence is reported.

	Longitudinal cracking	**Sticker Breakouts**	**Oscillation Marks**	**Transverse and Corner Cracking**	**Star Cracking**
Mould level	X				
Mould powder	X	X	X	X	X
Mould friction				X	
Mould taper	X			X	
Mould oscillation	X	X	X	X	
Casting Speed	X		X	X	X
Temperature	X	X	X	X	X
Composition	X	X	X	X	

Table 7-1: Defects occurrence [re-adapted from F.R. Caminsani et al. "A review of causes of surface defects in continuous casting", IFAC Proceedings Volumes, Volume 36, Issue 24, 2003,113-121,]

Table 7-2 reports instead a summary of cracks related to powder practice

Crack Type	Susceptible grades	Best Powder Practice
Longitudinal cracking	Medium-Carbon Peritectics	High thermal resistance, thick crystalline slag layer
Longitudinal corner cracking	Medium-Carbon Peritectics	High thermal resistance, thick crystalline slag layer
Sticker Breakouts	High Carbon	Low viscosity glassy slag
Oscillation Marks	In general	Thick crystalline slag will help but oscillation practice is much more critical
Transverse and Corner Cracking	Peritectic, Micro-alloyed, Low-Carbon	High thermal resistance, thick crystalline slag layer
Star Cracking	Peritectics	High thermal resistance, thick crystalline slag layer

Table 7-2: Cracks related to powder practice

7.8 References Appendix B

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8 List of figures and tables