

## **The Working Group “Continuous Casting: Metallurgy and Materials (M<sup>2</sup>CC)” at Leoben University, Austria**

Christian Bernhard, Robert Pierer, Sebastian C. Michelic  
University of Leoben,  
Franz-Josef-Straße 18,  
8700 Leoben, Austria,  
E-mail: christian.bernhard@mu-leoben.at

Key words: Continuous Casting, Defect Formation, Peritectic Phase Transition, New Casting Processes, Numerical Simulation

### **INTRODUCTION**

The working group M<sup>2</sup>CC is a part of the Chair of Metallurgy at Leoben University in Austria. Leoben University was founded in 1840 in Upper-Styria, one of the centers of Iron- and Steelmaking in the former Austrian-Hungarian Monarchy. At the very beginning, research as well as study programs were mainly focusing on ferrous metallurgy and mining. Today, Leoben University offers 9 degree programs for 2.500 students. The core areas cover the exploitation and dismantling of mineral resources, the environmental protection and waste disposal technology, petroleum engineering, plastics engineering, metallurgy and materials science.

The Chair of Metallurgy performs research on reduction metallurgy, steelmaking processes, secondary steelmaking and steel cleanliness, continuous casting, welding and also on the development and application of new steel grades.

The development of the working group M<sup>2</sup>CC is intimately connected with the name of the late Manfred Wolf. He became lecturer for “Continuous Casting Technology” at the Chair of Metallurgy in the early 1990s and attained an accredited lectureship in “Continuous Casting” in 1996. His habilitation thesis is still a standard work on the solidification of peritectic steels<sup>1</sup>. Manfred Wolf became the mentor of the continuous casting research activities at the Chair of Metallurgy until his early passing in 2001.

In 2001 the proposal for the establishment of a Christian Doppler Laboratory (CD-lab) on “Metallurgical Fundamentals of Continuous Casting Processes” (CDL-MCC) was – after a reviewing process by international peers – approved by the Christian Doppler Research Foundation (CDG). The aim of the CDG is the promotion of innovative research in the areas of natural sciences, technology and economics and of their application in the commercial sector<sup>2</sup>. The association allows the establishment of small to medium-sized research groups (laboratories) under the leadership of selected scientists. These units perform research in collaboration with member company partners of the CDG. The labs have to address both specific, application-oriented research activities and further developments in basic science. This model is an effective and uncomplicated instrument for creating the framework for a long-term collaboration between scientists and companies. A CD-lab is financed by its company partners and by public funding at equal shares. The duration of a CD-lab is limited to 7 years.

CDL-MCC addressed different research topics in the field of continuous casting in 5 different so-called “modules”:

- Numerical simulation of initial solidification in the mold and of the formation of centre segregation in the continuous casting of blooms;
- Microstructure and defect formation in the continuous casting of steel;
- Strip casting of carbon steels;
- Development of alternative light-weight steels and
- Influence of interfacial properties on the clogging phenomenon.

The main industrial partners of CDL-MCC at that time were *voestalpine Stahl*, *Siemens-VAI Metals Technologies*, *voestalpine Stahl Donawitz*, and *RHI*. CDL-MCC became the nucleus of the working group MCC, also participating in different other – national as well as international – projects. In 2006, 7 PhD students, 2 technicians and a number of undergraduate and graduate students contributed to the success of the working group. The contract for CDL-MCC ended with the end of 2009.

Already in 2008, a new research program for “Competence Centers for Excellent Technologies” (COMET) was established by the Austrian Government and the Austrian Research Promotion Agency<sup>3</sup>. The Chair of Metallurgy and particularly the working group MCC participated in two of the new K-centers:

- The K2-center for “Integrated Research in Materials, Processing and Product Engineering”, located at Leoben University and the
- K1-center for “Advanced Metallurgical and Environmental Process Development” together with leading Austrian companies, like *voestalpine* or *Siemens VAI Metals Technologies*.

In 2009, the working group changed its name to Metallurgy-Materials-Continuous Casting (M<sup>2</sup>CC). Next to the participation in the newly established competence centers, M<sup>2</sup>CC takes part in different other national research programs and in bilateral projects with different – mainly Austrian – company partners. Two post-docs, 7 PhDs at Leoben University and the collaborating competence centers, 3 PhDs in industry and one PhD at a partner university together with 1 technician and a number of graduate students are involved in continuous casting research. In the following, the main research topics will be highlighted.

## DEFECT FORMATION IN CONTINUOUS CASTING

### Defect Formation during Solidification – Hot Tearing

At the beginning of the 1990s a laboratory experiment, which was later termed as Submerged Split Chill Tensile (SSCT) test, was adopted from EPF Lausanne. This university mainly carried out studies investigating the deformation behavior of solidifying Al-alloys<sup>4,5</sup>. At the Chair of Metallurgy in Leoben the experiment was applied on solidifying steel, continuously modified and improved and the testing procedure was systematized<sup>6,7</sup>.

A proper laboratory simulation to investigate defect formation during solidification (i.e. hot tearing) under continuous casting conditions needs to fulfill the following demands: (1) the existence of a deformable solid-liquid two phase region together with a columnar grain structure, (2) the conformity of the solidification structure with that of a continuous casting shell, and (3) main load directions that are perpendicular to the main dendrite growth axis. All of these demands are satisfied by the SSCT test together with a further big advantage in comparison to conventional hot tensile tests: During conventional hot tensile experiments the samples were fully ruptured and certain temperatures (zero strength and zero ductility temperature) must be defined in order to explain the measured strength and ductility above solidus. In fact, by defining the so called brittle temperature range on the basis of these temperatures, the proneness to hot tearing (i.e. a hot tearing sensitivity or hot tearing susceptibility) can be estimated, however, critical values (e.g. critical strain of hot tearing) can not be determined. This can be realized using the SSCT test. Moreover, the extent of hot tearing, expressed in terms of the number and length of the hot tears, can be correlated with the extent of deformation. Thus, it is possible to define critical strain values as a function of steel composition, strain rate and the solidification conditions and taking into account the demands on the final cast product.

Intensive collaborations with *Siemens VAI Metals Technologies* and *voestalpine Stahl* results in an entirely new understanding of the phenomenon of hot tearing, which will be summarized briefly in the following (for a detailed consideration the reader is referred to the corresponding paper and presentation of our working group at the present conference)<sup>8-14</sup>:

- Internal defect formation during continuous casting of steel results from a hot tearing process, i.e. the formation of a defect (hot tear) takes place above the solidus temperature within a certain temperature range between the liquidus and solidus temperature (solid/liquid two phase region). Two types of hot tears must be considered: hot tear segregations and open hot tears. The first type, sometime falsely termed as healed crack, appears similar to a crack optically. However, it represents a segregation phenomenon which must be described with respect to an extension (deformation) of the space between solidification grains (i.e. the primary grain boundaries).
- The formation of hot tear segregations results not from a refilling process of an open hot tear by an inflow of liquid. Results of a multiplicity of SSCT tests as well as results from analyzed hot tears generated during continuous casting indicate that hot tearing must be described as a sequence of (1) the formation of hot tear segregations (frequently accompanied with precipitations), (2) the formation of pores (partly open areas within the hot tear segregation) and subsequently (3) the coalescence of these pores to open hot tears. Thus, open hot tears must always be seen in conjunction with high segregation areas in their vicinity.
- Both types of hot tears may degrade the final product quality and must be considered with respect to (1) the three dimensional extension of hot tear segregations in combination with the enrichment of concentration, (2) the formation of nonmetallic inclusions (e.g. MnS or Nb-(CN) precipitations) within the hot tears segregations and (3) the spatial dimension of open hot tears (position within the continuously cast product) and their behavior during further processing.

- In the continuous casting process, the formation of hot tears can be described by strain accumulation within a certain temperature range of the solid/liquid two phase region. Using this criterion, steel composition, strain rate, solidification velocity, temperature gradient and the strain contribution due to thermal contraction (shrinkage) can easily be considered. In doing so, the term “effective strain” was introduced. It could be shown that with increasing effective strain, the number and length of hot tears increases. Since the critical extent of the deterioration (damage) ultimately depends on the demands on the final product quality, the criterion of an effective strain enables the definition of critical deformation limit as a function of number and length (i.e. the extent of hot tearing) of hot tears.

Typical hot tears in terms of hot tear segregations, which were generated by the SSCT test, are illustrated in Figure 1a. The white spots on the concentration mapping were used to mark the position within the sample. Due to the high enrichment of Mn within the hot tear segregation, the defects are clearly silhouetted against the typical solidification structure. The pictures on the right hand side show concentration mappings of b) Si, c) Mn, d) P and e) S (Detail A – Detail D) (Chemical Composition: 0.12 wt%C, 0.30 wt%Si, 1.35 wt%Mn, 0.007 wt%P and S). The different extent of the segregation can already be observed in hot tear segregations within one single sample.

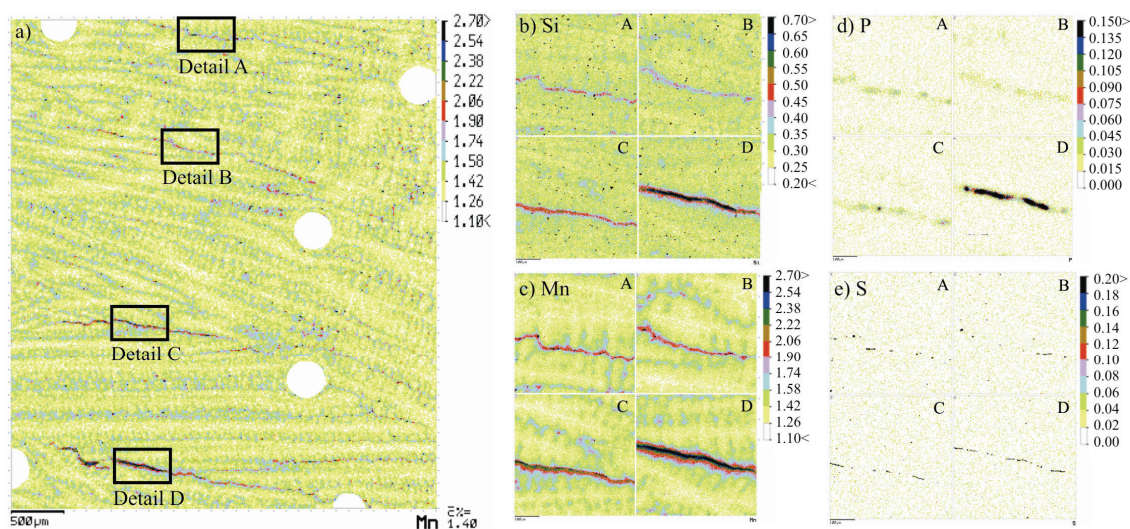


Figure 1. Concentration mapping of experimentally generated hot tear segregations (chemical composition: 0.12 wt%C, 0.30 wt%Si, 1.35 wt% Mn and 0.007 wt%P and S).

The implementation of our results and in particular the criterion of strain accumulation takes place within a project of the K1-centre “Advanced Metallurgical and Environmental Process Development” together with leading Austrian companies, like *voestalpine Stahl* or *Siemens VAI Metals Technologies*. The improvement of the understanding of hot tearing as well as the consideration of the solidification structure on critical values of hot tearing will be treated within the K2-centre for “Integrated Research in Materials, Processing and Product Engineering”, located in Leoben.

### In-Situ Material Characterization – Surface Crack Formation at Elevated Temperatures

Transverse cracks are one of the most popular surface defects which may develop in the temperature range of the second ductility trough during continuous casting of steel. According to the relevant literature, this kind of crack formation is commonly associated with a low ductility due to precipitation and ferrite formation at the austenite grain boundaries in conjunction with occurring stresses and strains at the surface by strand straightening. One of the most frequently used laboratory experiment to simulate this phenomena is the hot tensile test. However, this method shows some disadvantages with respect to the reproduction of the continuous casting conditions, even the as-cast structure, the austenitic grain size as well as the amount of distribution of precipitations. Additionally, during the hot tensile tests recrystallization and the formation of deformation induced ferrite at austenitic grain boundaries takes place. This is in contrast to continuous casting of steel, where these phenomena are rather unlikely. The reason therefore can be found in the low deformation (2–4 %) and the coarse austenitic grains.



Figure 2. The IMC apparatus (left picture) which allows two different in-situ testing procedures (right pictures): the in-situ tensile test and the in-situ bending test.

Hence, a new method – the in-situ material characterization (IMC) test – has been developed in order to characterize the behavior of steels at elevated temperatures. This worldwide unique experimental technique allows to adjust the initial cooling conditions and thus the coarse columnar grain growth comparable to those in the continuous casting process, to restrict the total strain and the generation of a coarse columnar structure (prevention of dynamic recrystallization during loading) and to measure critical limits of defect formation (critical strain) directly. Furthermore, the IMC test can be used to conduct either in-situ hot tensile tests<sup>15</sup> or in-situ bending tests. In both cases, samples which directly solidified from the melt will be deformed. Figure 2 shows the IMC apparatus together with the two possible testing procedures. All of these facts represent a big step forwards in investigating mechanical properties for in-situ solidified steel samples, especially crack mechanisms under continuous casting conditions. The research activities of this project started last year (October 2009) within the framework of the K2-centre for “Integrated Research in Materials, Processing and Product Engineering”, located in Leoben.

### Defects Associated with the Peritectic Phase Transition

Continuous casting of peritectic steels is often difficult and critical; bad surface quality, cracks and even breakouts are feared. It is well known that the critical solidification behavior (e.g. uneven shell growth), may result in e.g. the formation of surface depressions during initial solidification. Consequently, a high sensitivity to the formation of surface and subsurface cracks can be observed. This behavior is attributed to the remarkably higher contraction during and immediately after solidification of peritectic steels due to the  $\delta\gamma$  transition. As commercial steels are always multi-component alloys, it is necessary to account also the influence of alloying elements besides carbon on the peritectic phase transition.

The aim of a project within the K2-centre for “Integrated Research in Materials, Processing and Product Engineering”, located in Leoben, is to investigate and characterize the peritectic phase transition in new steels with higher Al and Si content. The challenge of this topic is the experimental characterization of this high temperature phase transformation between the liquidus and solidus temperature. Thus, the investigations are carried out using different experimental methods, even commercial differential thermal analysis (DTA) and thermodilatometric analysis (DIL) to obtain the transformation temperatures with high accuracy. In order to describe and observe the sequences of solidification of the peritectic phase transition, the alloys will be characterized in-situ using a high temperature laser scanning confocal microscope (HTLSCM). In order to achieve a maximum of practical relevance to the continuous casting process the contraction during solidification and subsequent cooling is measured by a self-designed in-situ experiment, the so called Submerged Split Chill Contraction (SSCC) test; a modified test body of the SSCT test. The different used methods are illustrated in Figure 3.



All of these experimental investigations and the combination of differential techniques will help to increase the knowledge about the composition and temperature of the critical peritectic range. This result will enhance the CC process – and the final product quality of new steel grades.

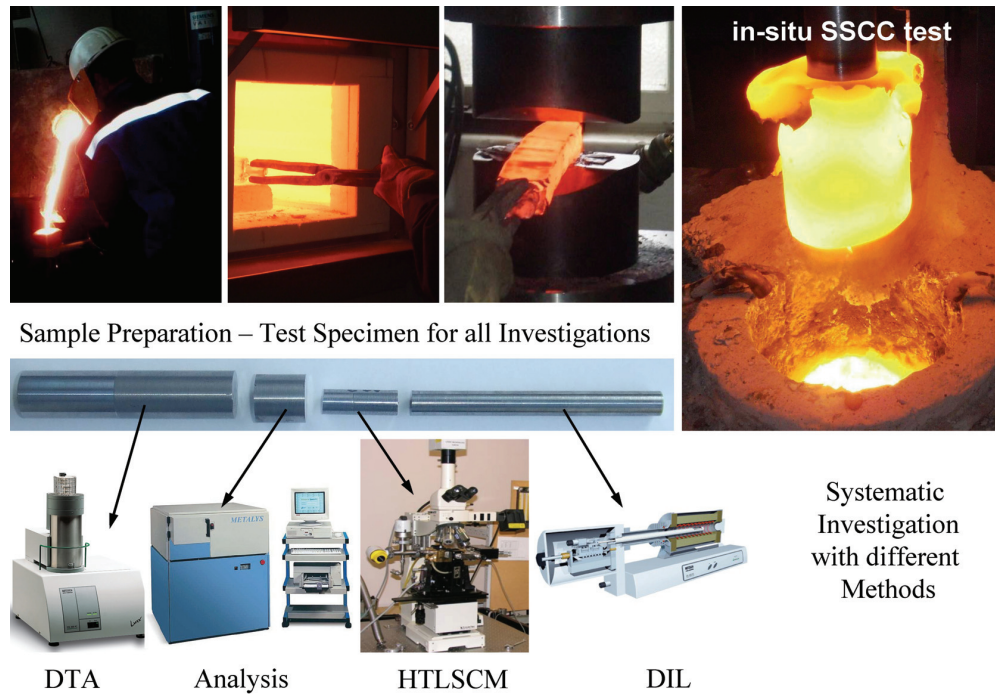


Figure 3. Different methods used to investigate the initial solidification behavior (SSCC) and the peritectic phase transition of steels.

### NEW CASTING PROCESSES FOR NEW STEEL GRADES

The work on new casting processes mainly focuses on solidification processes at higher cooling rate (see Figure 4). Thin strip casting, thin slab casting and rolling as well as welding are contents of projects in collaboration with industrial partners. The question of the castability of newly developed alloys in the continuous casting process is a further central point of interest.

#### Strip Casting of Carbon Steels

In 2002, CDL-MCC started to work on the experimental simulation of initial solidification in the strip casting process. *Siemens VAI Metals Technologies* and CDL-MCC jointly developed a simulation experiment that bases on the principle of a dipping test, as for example already realized by Mahapatra *et al.*<sup>16,17</sup> in the 1990s. Figure 5 shows the developed dipping experiment with rapid solidification and controlled cooling. A substrate, made from a conventional mold copper alloy – coated with Cr or Ni and with controlled surface roughness – is submerged into a steel melt at high velocity. The experiment is performed inside a vacuum induction furnace under shielding gas. The rectangular substrate is surrounded by a non-wetting, insulating refractory brick that prevents the solidification of the steel. Thus, a rectangular sample solidifies at the surface of the substrate under conditions close to the simulated process. During the dwell time in the melt – typically ranging from 0.25 s to 10 s (depending on the simulated process) – the shrinkage of the thin sample induces friction forces between the sample and the substrate. The main objective of the first experiments was to study the influence of testing parameters like surface roughness and coating material, shielding gas or solidification time on microstructure and the formation of surface micro cracks.

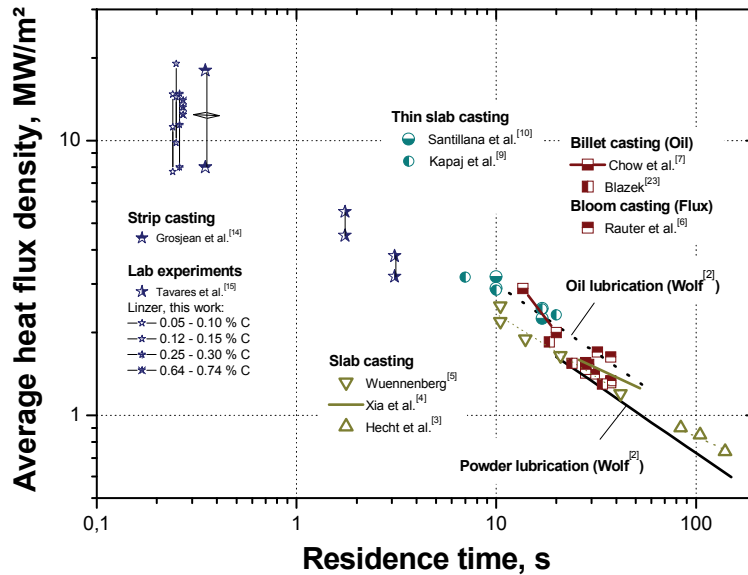


Figure 4. Average heat flux vs. residence time in mold for different casting processes.

The results show that the microstructure is equivalent to that of a solidified strip and – in certain cases – the microsegregation is less pronounced compared with conventional solidified material. The micro crack sensitivity considerably depends on the combination of steel composition and solidification parameters<sup>18</sup>. An adjustment of the steel composition in order to minimize the micro crack sensitivity is possible<sup>19</sup>.

A recently published work describes the adoption of the experiment for the simulation of the subsequent heat treatment of the rapidly solidified sample in order to quantify the resulting mechanical properties. It could be shown that the mechanical properties of HSLA steel are of the same value as those of conventionally produced steels<sup>20</sup>.

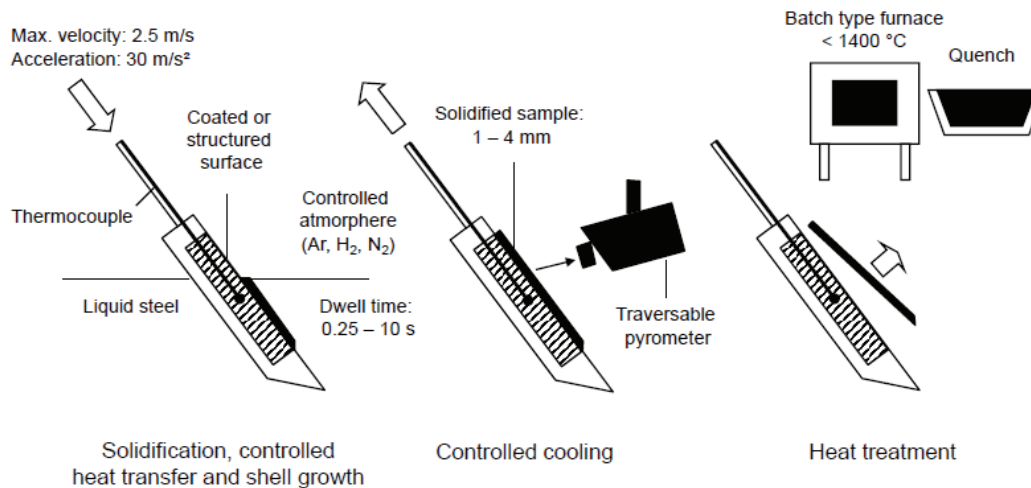


Figure 5. Dipping experiment with rapid solidification and controlled cooling.

### Thin Slab Casting and Rolling

In 2009, M<sup>2</sup>CC started the collaboration with *Siemens VAI Metals Technologies* on the Arvedi-ESP-process<sup>21</sup>. Part of M<sup>2</sup>CC in this joint research project is the development of a microstructure model for the continuous casting part of an ESP-plant. This model

includes a solidification model, a microsegregation model, an austenite grain growth model<sup>22</sup> and a precipitation model. Main objective is to define the initial state of the thin slab before the entry into the hot rolling mill.

The above described experiment was further adopted in order to simulate the solidification in a thin slab casting mold at casting speed of up to 7 m/min. The further cooling of the surface in the secondary cooling zone will also be adjusted in the experiment. The models for solidification, grain growth and precipitation will be fitted to the experimental results.

### Further Research Projects

The other fields of activity comprise a number of different projects:

- The development of welding rods for the welding of high strength steels in collaboration with *Boehler Welding*,
- The development of melting and casting techniques for high-Manganese steels for shape memory applications,
- And the development of casting techniques for the casting of lightweight steels.

## NUMERICAL SIMULATION OF SOLIDIFICATION – COMPUTATIONAL CASTING

Numerical simulation of solidification has become indispensable for a detailed study of the ongoing mechanisms during solidification – in laboratory trials as well as in industrial practice. It is well accepted that numerical simulation of solidification not only requires the application of appropriate algorithms but also the detailed determination of thermal boundary conditions for every solidification process. Both issues have frequently been addressed in different projects; some of the results are described in the following.

### Solidification Models for Bloom Casters

During the contract time of CDL-MCC two projects aimed at creating process-related solidification models for the bloom casters installed at *voestalpine Stahl Donawitz* were conducted. In a first project, an axisymmetric finite-volume model for the round bloom caster was created. This model, which features all-time availability for the industrial partners, allows the computation of the thermal states and the solidification conditions for the whole casting process as a function of steel grade, casting conditions and cooling parameters. Thus, a tool which allows an independent use of numerical methods for process optimization was created for the industrial partner.

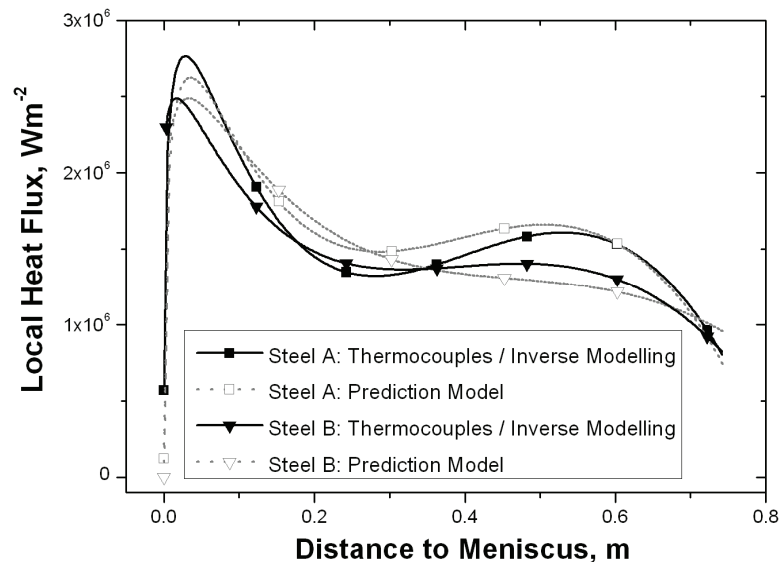


Figure 6. Local heat flux determined via thermocouple measurements and subsequent inverse modeling and by the prediction model in<sup>24</sup> for a medium carbon steel (Steel A) and a high carbon steel (Steel B).

One of the key issues which were identified in this respect is the determination of thermal boundary conditions. Several measurement campaigns with molds instrumented with thermocouples were performed in order to determine the local heat withdrawal in the mold via inverse numerical modeling. A summary of relevant publications can be found in<sup>23</sup>. Based on an additional mold flux consumption model, predictions on the heat flux in round molds can now be made<sup>24,25</sup>. Results of the model can be found in Figure 6 which shows the comparison of the local heat flux of the mentioned prediction model together with values computed from temperature measurements in instrumented molds for a medium carbon steel (Steel A) and a high carbon steel (Steel B). Evidently, considerable differences can be identified; owing to their influence on the solidification conditions in the casting process, the identification and application of carefully determined and multiply validated boundary conditions is of significant importance for such natured process models.

In a second project, a similar solidification model was created for a rectangular bloom caster. An example of the results of a fully three-dimensional simulation is shown in Figure 7. Since the computation of such results is inflicted with a tremendous computational load, special algorithms which permit a nearly equivalent transient two-dimensional treatment of the problem were developed. The employed algorithm (called the Modified Alternating Direction Implicit Method) now offers a complete simulation of the solidifying strand in a highly attractive runtime<sup>26</sup>. Additionally, thermal boundary conditions were also derived in the course of the development of this model. Again using an instrumented mold, considerable know-how was built up in the field of transient two-dimensional inverse modeling. Thus, the solidification model for the rectangular bloom caster is based in a large number of in-process determined boundary conditions in the mold area.

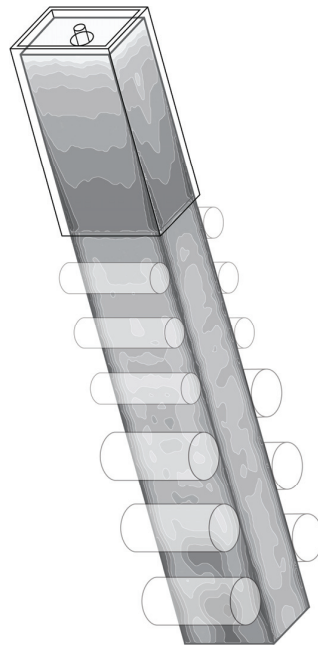


Figure 7: Surface temperature distribution in a solidifying bloom; the strand support is schematically depicted by the support rolls.

### Thermal Boundary Conditions for Spray Cooling

Next to finding thermal boundary conditions in the mold area, the difficulty of creating process-close solidification models lies in determining the heat withdrawal in the secondary cooling zones, i.e. due to spray cooling. Although numerous dependencies of the heat flux on the water impact density can be found in the literature, their broad scattering indicates a small range of validity of the single dependencies. Moreover, surface temperature measurements with optical methods (pyrometers) or dragged thermocouples are also inflicted by inaccuracy due to the formation of scale in the first case or the loss of contact in the second.

Therefore, M<sup>2</sup>CC is currently constructing a new two-dimensional nozzle measuring stand which allows for the experimental determination of the heat withdrawal during spray cooling as a function of water and air pressure, position of the nozzle, surface temperature, etc. First very promising results indicate that the measurement set-up is highly capable of reproducing the complex interactions between cooling and solidification. Publications on the measurement principle and first results will follow in due course.

The combination of the algorithms mentioned in the previous section, the know-how on mold heat withdrawal and the innovative nozzle measuring stand now puts M<sup>2</sup>CC in the position of being able to model solidification in continuous casting at a highly process-near level.



## Polydimensional Multicomponent Microstructure Modeling

A further asset in M<sup>2</sup>CC's possibilities in modeling solidification is a recently developed two-dimensional, multicomponent microstructure model. Based on the virtual-front tracking technique, solidification can thus be studied on the level of dendrites. The model formulation has been published lately<sup>27</sup>; the model features the computation of columnar and equiaxed solidification for a wide range of simulation possibilities. A result of the model can be found in Figure 8, which shows the detail of columnar solidification simulation in a Fe-0.6 wt%C-0.5 wt%Si-0.5 wt%Mn alloy by the Si-distribution at different simulation times.

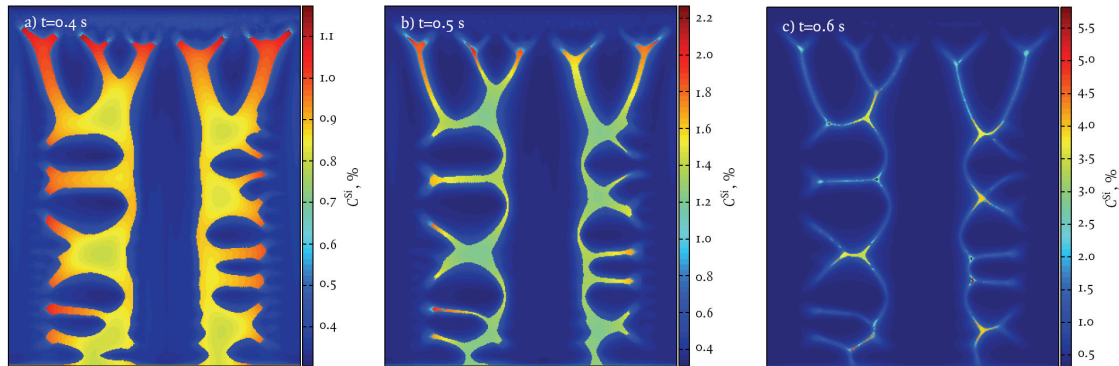


Figure 8. Si-distribution in wt% during columnar solidification for different solidification times. Details to the simulation can be found in<sup>27</sup>.

## SUMMARY

Continuous casting research has a long tradition at the Chair of Metallurgy (CoM): Already in the 1950s metallurgists from CoM worked on the development of the continuous casting process in collaboration with Austrian steel producers. In the 1990s, Manfred Wolf became associate professor for continuous casting and the activities were intensified further. In 2002, the Christian Doppler laboratory for “Metallurgical Fundamentals of Continuous Casting Processes” was established and today, the working group “Continuous Casting: metallurgy and materials (M<sup>2</sup>CC)” focuses on three main activity fields:

- Defect formation in the continuous casting process,
- New casting processes for new steel grades,
- Computational casting.

Besides the activities with partners from industry, M<sup>2</sup>CC defines itself as part of a scientific network: The working group is closely connected with other working groups at CoM and the University of Leoben. Together with the working group « Steel cleanliness » at CoM, M<sup>2</sup>CC works in cooperation on issues like « Clogging in continuous casting », for example. Within the framework of different national funded projects, M<sup>2</sup>CC collaborates with institutes from all technical universities in Austria. M<sup>2</sup>CC also collaborates with international scientific partners, e.g. from Germany, USA and Australia and will further expand these activities in future.

## REFERENCES

1. M. Wolf, “Initial solidification and strand surface quality of peritectic steels”, *Continuous Casting*, Vol. 9, Warrendale, USA, 1997.
2. Programme Document for the Christian Doppler Research Association, BMWA-97.430/0011-C1/9/2007, Version 2008 09 08 (Available for download on [www.edg.ac.at](http://www.edg.ac.at)).
3. Programme Document for the New Programme for Competence Centres COMET: Competence Centres for Excellent Technologies, Version 2008 06 01, (Available for download on [www.ffg.at](http://www.ffg.at)).
4. P. Ackermann, W. Kurz and W. Heinemann, “In situ tensile testing of solidifying aluminum and Al-Mg shells”, *Materials Science and Engineering*, Vol. 75, No. 1-2, 1985, pp. 79-86.
5. J. D. Wagnieres and P. Ackermann, Le laboratoire d’aujourd’hui pour les brames de demain, *La Revue Politechnique*, Vol. 6, 1985, pp. 669-673.

6. C. Bernhard, M. M. Wolf and H. Hiebler, "Simulation of shell strength properties by the SSCT test", *ISIJ International, Suppl. Science and Technology of Steelmaking*, Vol. 36, 1996, pp. 163-166.
7. H. Hiebler and C. Bernhard, "Mechanical properties and crack susceptibility of steel during solidification", *Steel Research*, Vol. 69, No. 8+9, 1999, pp. 349-355.
8. R. Pierer, S. Michelic, C. Bernhard and C. Chimani, "A hot tearing criterion for the continuous casting process", *METEC InSteelCon, Third International Conference on New Developments in Metallurgical Process Technologies*, Düsseldorf, Germany, 2007, pp. 893-900.
9. C. Bernhard, R. Pierer, and C. Chimani, "A new hot tearing criterion for the continuous casting of steel", *5th Decennial International Conference on Solidification Processing*, Sheffield, UK, 2007, pp. 525-530.
10. R. Pierer, C. Bernhard and C. Chimani, "A contribution to hot tearing in the continuous casting process", *La Revue de Metallurgie*, No. 2, 2007, pp.72-83.
11. R. Pierer, S. Griesser, J. Reiter and C. Bernhard, "On the formation of hot tear segregations in steel: Metallographic Analysis and Characterization", *BHM*, Vol. 154, No. 7, 2009, pp. 346-353.
12. C. Bernhard, "Über Zusammenhänge zwischen Prozess und Produktqualität beim Stranggießen von Stahl am Beispiel der Heißbrissbildung", *Postdoctoral Thesis*, Chair of Metallurgy, University of Leoben, 2007.
13. C. Bernhard, "Anforderungen an prozessorientierte Heißbrissbildungsmodelle", *BHM*, Vol. 149, No. 3, 2004, pp. 90-95.
14. S. Ilie, J. Reiter, J. Fluch, H. Presslinger and C. Bernhard, "Characterization of hot tear segregations in continuous casting of slabs", *6th European Continuous Casting Conference*, Riccione, Italien, 2008, Presentation No. 122.
15. A. Tubikanec, C. Chimani and C. Bernhard "The newly developed In-situ Material Characterization (IMC-) test: installation, start-up and first results", *6th European Continuous Casting Conference*, Riccione, Italien, 2008, Presentation No. 86.
16. W. Blejde, R. Mahapatra and H. Fukase, "Development of low carbon thin strip production capability at Project M", *Iron- and Steelmaker*, Vol. 27, No. 4, 2000, pp. 29-33.
17. K. Mukunthan, L. Strezov, R. Mahapatra and W. Blejde, "Evolution of microstructures and product opportunities in low carbon steel strip casting", *Canadian Metallurgical Quarterly*, Vol. 40, No. 4, 2001, pp. 523-532.
18. B. Linzer, C. Bernhard and G. Hohenbichler, "Experimental simulation of strip casting", *BHM*, Vol. 149, 2004, pp. 107-111.
19. C. Bernhard, G. Eckersdorfer, G. Hohenbichler and B. Linzer, "Method for producing a steel strip", *Patent, WO 2008/034502A1*, 2008 03 27.
20. B. Linzer, G. Hohenbichler, S. Bragin, G. Arth and C. Bernhard, "Experimental simulation of the solidification of steel at higher cooling rate", *3rd International Conference on Simulation and Modeling of Metallurgical Processes in Steelmaking*, Leoben, Austria, 2009, Paper - CC17.
21. J. Siegl, G. Holleis, A. Angerbauer, "The Arvedi Endless Strip Production line (ESP) - from liquid steel to hot-rolled coil in seven minutes", *17th Rolling Conference*, Santa Fe, Argentina, 2008 pp. 67-76.
22. C. Bernhard, J. Reiter and H. Preßlinger, "A model for predicting the austenite grain size at the surface of continuously cast slabs", *Metallurgical and Materials Transactions B*, Vol. 39, 2008, pp. 885-895.
23. C. Bernhard, "Continuous casting research at the Chair of Metallurgy: Past, Present, Future", *BHM*, Vol. 154, No. 1, 2009, pp. 20-26.
24. S. Michelic, C. Bernhard and R. Pierer, "Numeric modeling of the heat transfer in the continuous casting mold", *SteelSim*, Graz/Seggau, Austria, 2007, pp. 209-215.
25. W. Rauter, M. Erker, W. Brandl, S. Michelic and C. Bernhard "Heat transfer in a round CC mold: measurement, modeling and validation", *6th European Continuous Casting Conference*, Riccione, Italien, 2008, Presentation No. 30.
26. S. Michelic, C. Bernhard, W. Rauter, M. Erker and A. Sormann, "Modeling solidification in continuous casting: algorithms and boundary conditions", *3rd International Conference on Simulation and Modeling of Metallurgical Processes in Steelmaking*, Leoben, Austria, 2009, pp. 1-8.
27. S. Michelic, J. M. Thuswaldner and C. Bernhard, "Polydimensional modeling of dendritic growth and microsegregation in multicomponent alloys", *Acta Materialia*, 2010, in press.