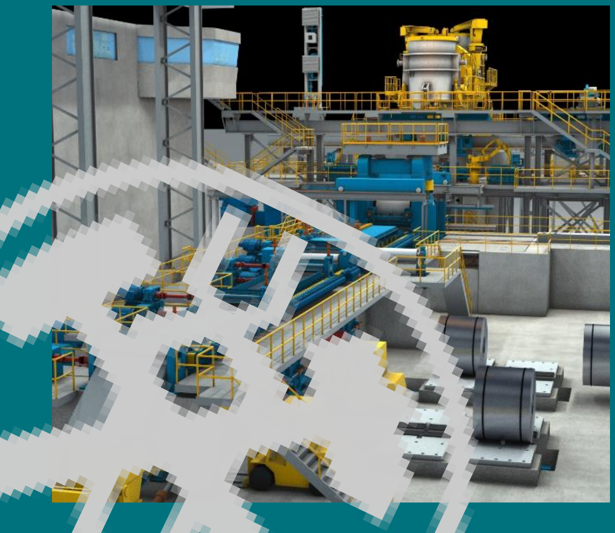
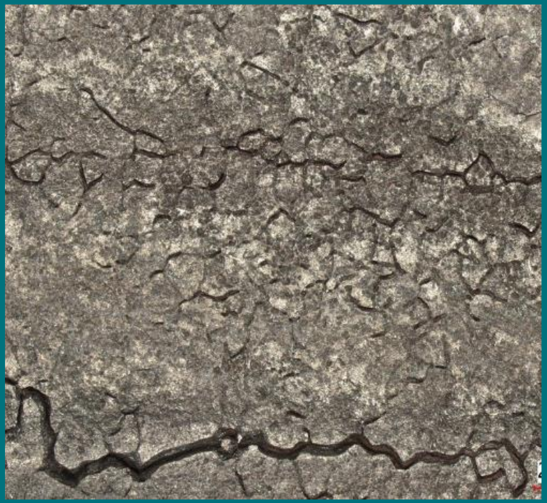
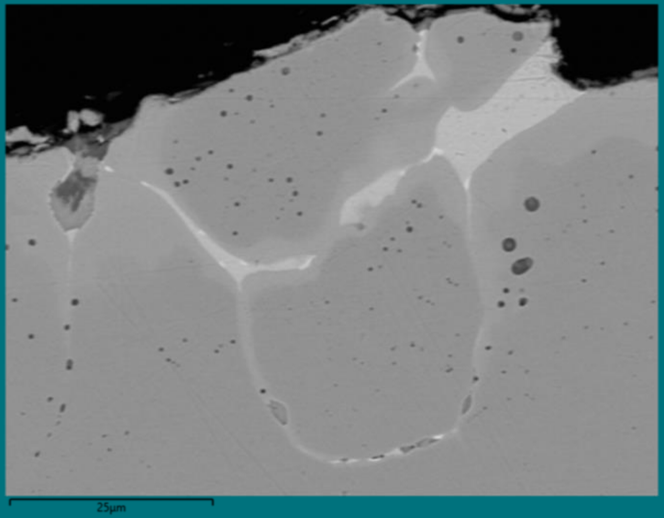
Technical University Leoben
Ferrous Metallurgy

From phenomenological models to hybrid approaches: quality prediction in continuous casting at a crossroads.

Christian Bernhard, Susanne Hahn and Sergiu Ilie
Michael Bernhard, Peter Presoly, Georg Gaiser, Maximilian Kern, Robert Littringer, Daniel Kavić

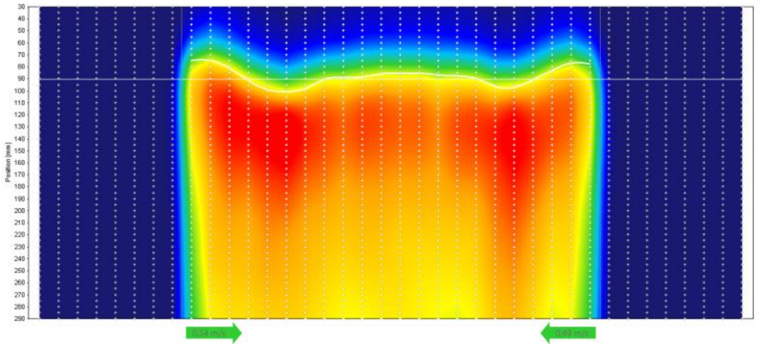
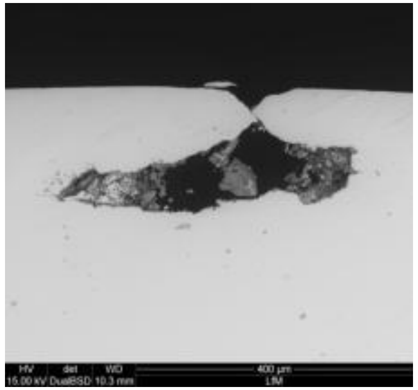
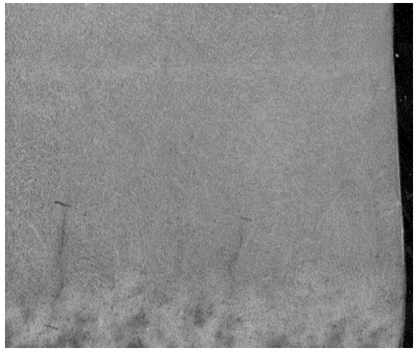
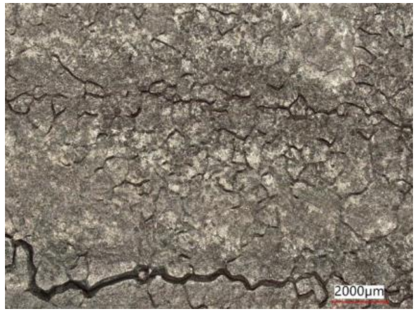
6th K1-MET Simulation Conference, Vienna, 2025



Agenda

- **Introduction**
- **Quality in the context of the continuous casting process**
  - Steel Cleanness
  - Internal Defects
  - Surface Defects
- **New ways of quality prediction – „hybrid appproach“**
  - Internal cracking
  - Surface cracking
  - … and what about experiments?
  - … and what about new sensors?
- **Conclusions**

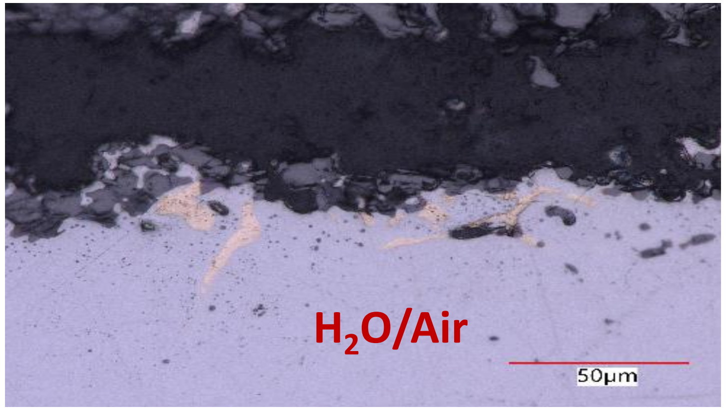





Introduction

Introduction: Funded projects on quality prediction/control

- **Projects addressing cc product quality within K1-MET**

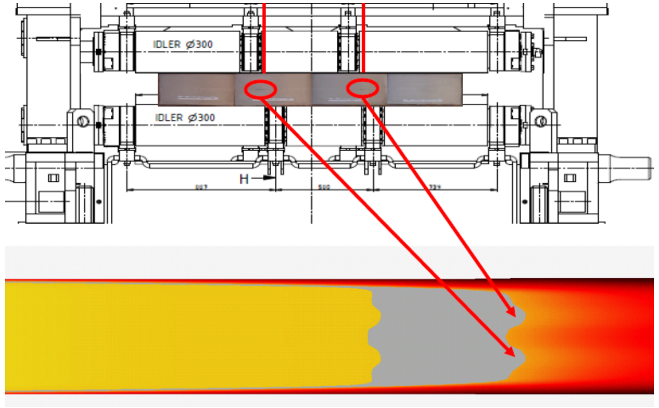
  - K1-1.4: **Sustainable continuous casting process**
    - WP 1: CC product surface quality prediction and impact of a decarbonized process on steel castability.
    - WP 2: Smart quality prediction for continuous casting by a hybrid approach (HYCast).
  - K1-3.4: **Hybrid Modelling**
    - WP 6: Hybrid Mold - Data evaluations around the continuous casting process.



PRIMETALS TECHNOLOGIES

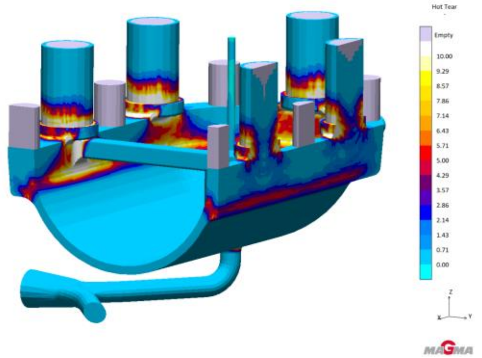
voestalpine ONE STEP AHEAD.

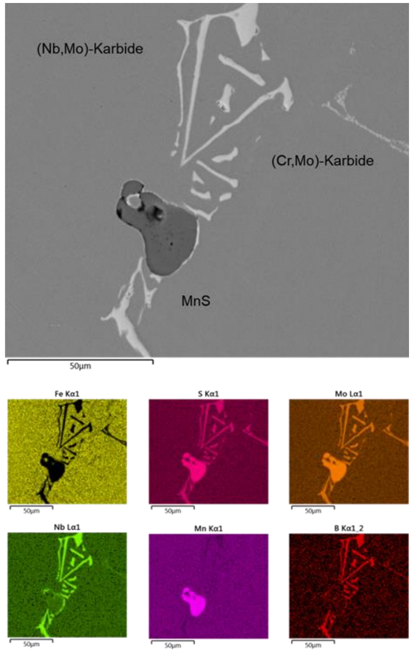
Ternium



- **Projects within K2-MPPE**

  - K2- Casting QPS: Advanced Casting Quality Prediction Systems for predicting the quality of continuous cast slabs and of heavy steel castings.
  - K2-ESP Next: ESP-Next generation green steel.





MAGMA Committed to Casting Excellence

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Quality in the context of the continuous casting process

- **Quality Requirement, examples:**

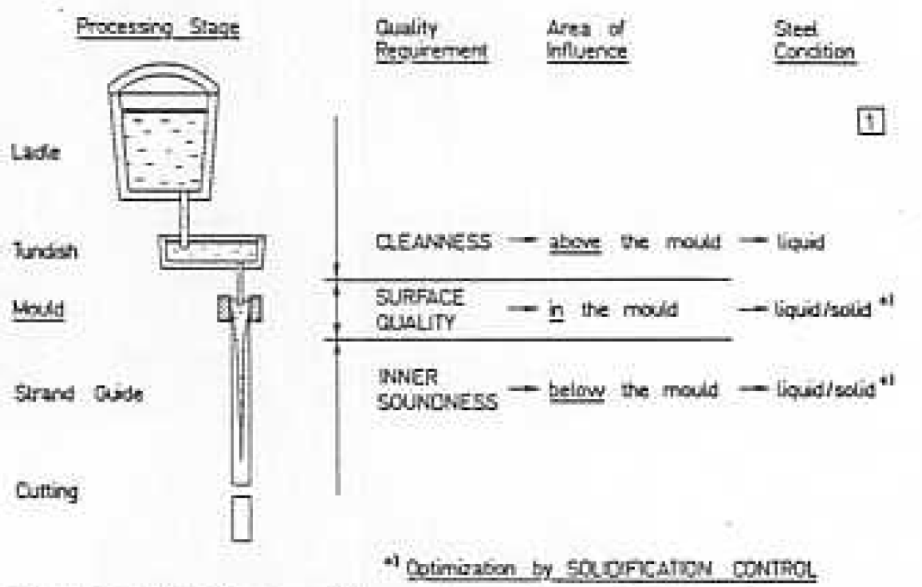
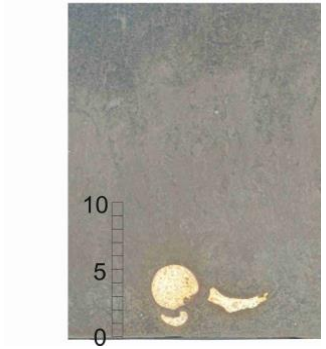


Figure 1. Product quality requirements related to the process stages in continuous casting [1])

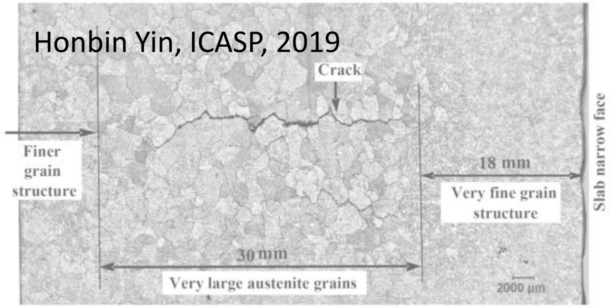
M. Wolf, Elements of solidification control in the cc of billets and blooms, MPT 1983.

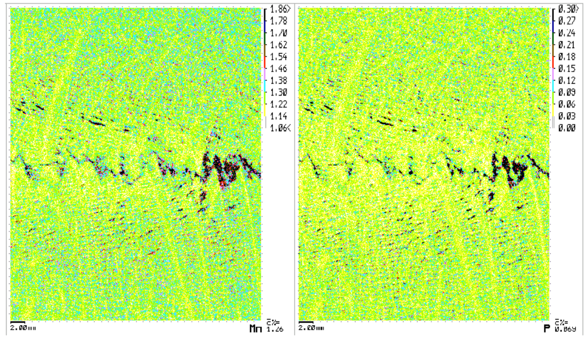
Quality in the context of continuous casting

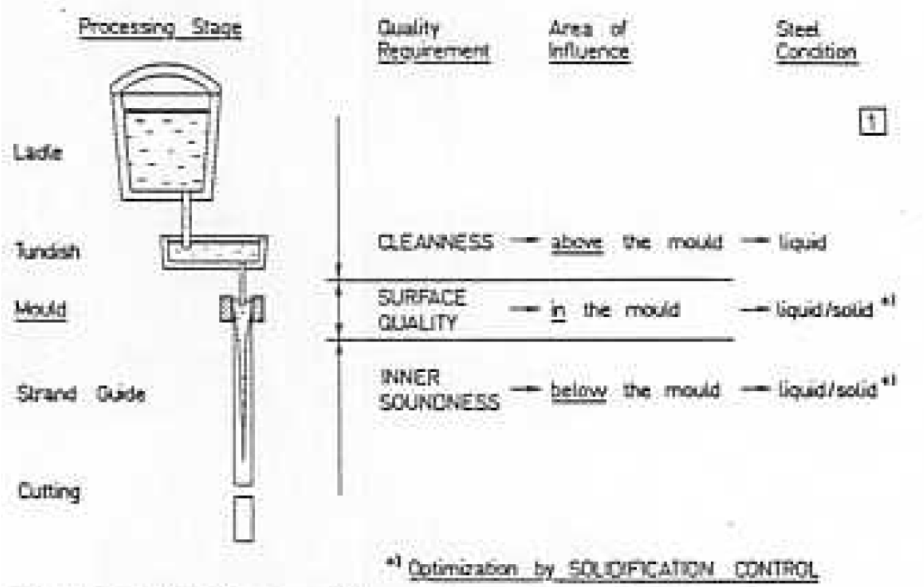
- **Quality Requirement, examples:**
  - **Steel Cleanness**
    - Nonmetallic Inclusions (NMI).
    - Entrapment of slags, sands and lining.
  - **Surface Quality**
    - Slivers.
    - Oscillation marks.
    - Depressions.
    - Surface cracking.
    - ….
  - **Inner Soundness**
    - Center segregation.
    - Hot tearing.



Honbin Yin, ICASP, 2019







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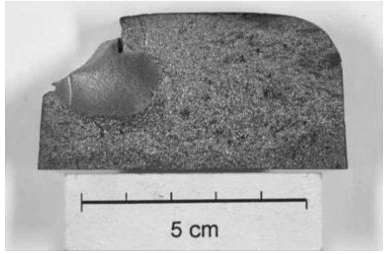
Presslinger, H., S. Ilie, et al. 12th ISIJ-VDEh-Seminar, November 21-22 2005, Kitakyushu, Japan, 125-134

Quality in the context of continuous casting

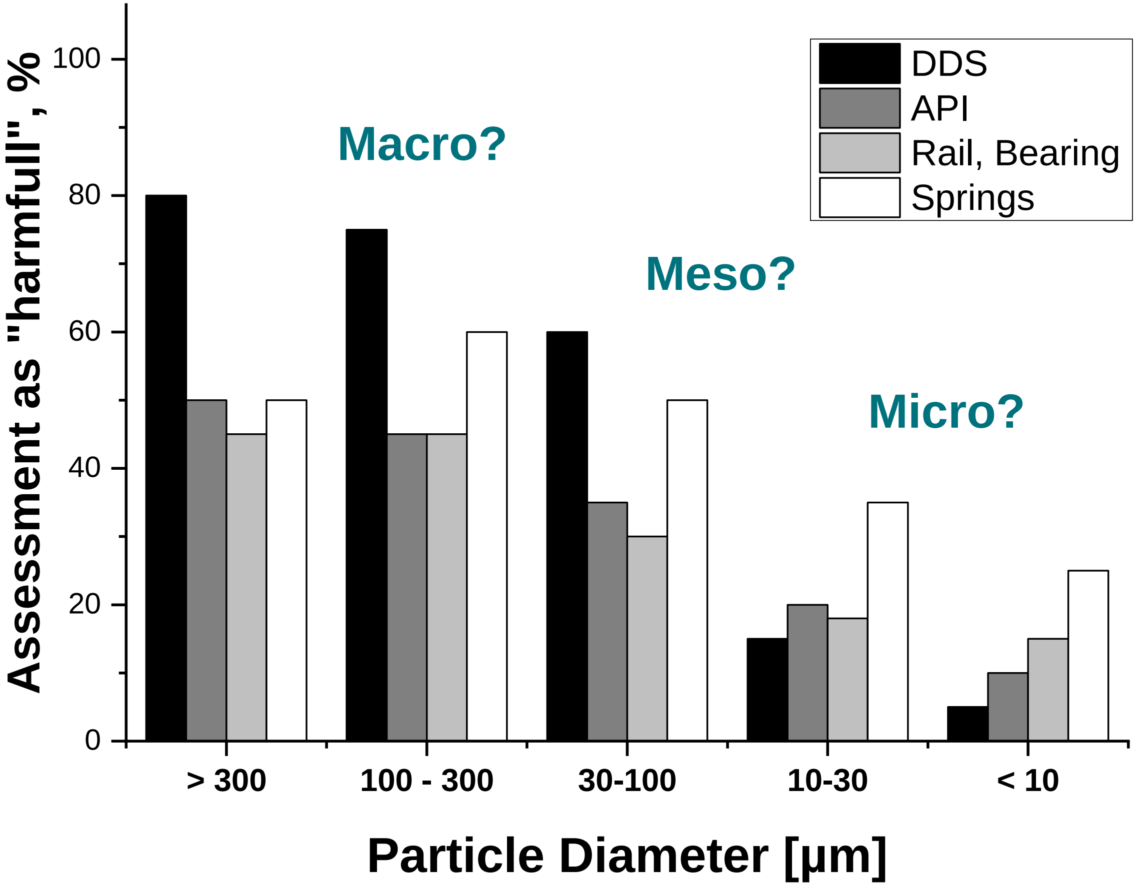
- **Non-metallic phases/inclusions**
- **Industrial practise: What makes a non-metallic inclusions harmful?**



Fatigue fracture of a rail due to macro-inclusions

Hydrogen induced cracking in API

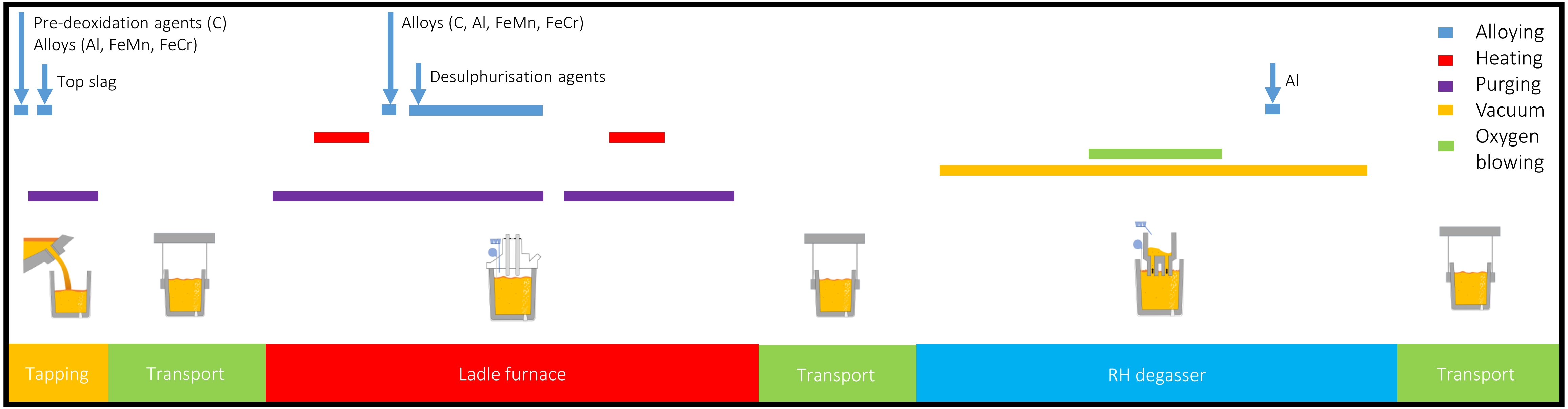
Source: Kloesch, 2009



Source: IISI Study on Clean Steel, 2004

Quality in the context of continuous casting

- **K1-1.5: I-Clean: Hybrid modelling** of ladle treatment with emphasis on composition of steel and slag, temperature, and inclusions.



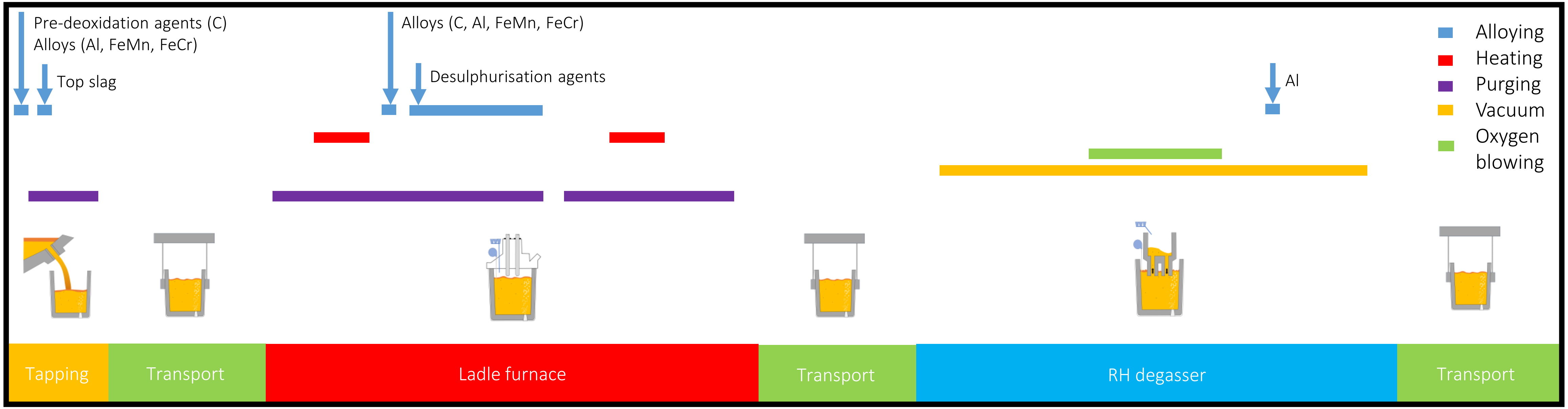
Quality in the context of continuous casting

- **K1-1.5: I-Clean: Hybrid modelling** of ladle treatment with emphasis on composition of steel and slag, temperature, and inclusions.

White box: Mechanistic models. Heat and mass transfer + computational thermodynamics in ChemApp (FactSage)

Grey box: The best from both worlds „I-Clean“

Black box: Data-driven approaches (e.g. regression modeling). Process data (Composition of steel, slag, inclusions and temperature)



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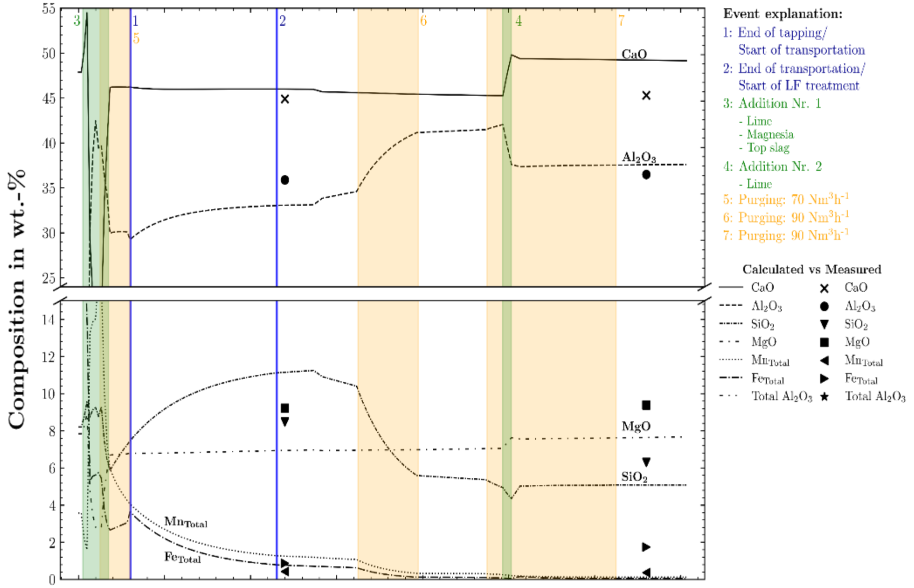
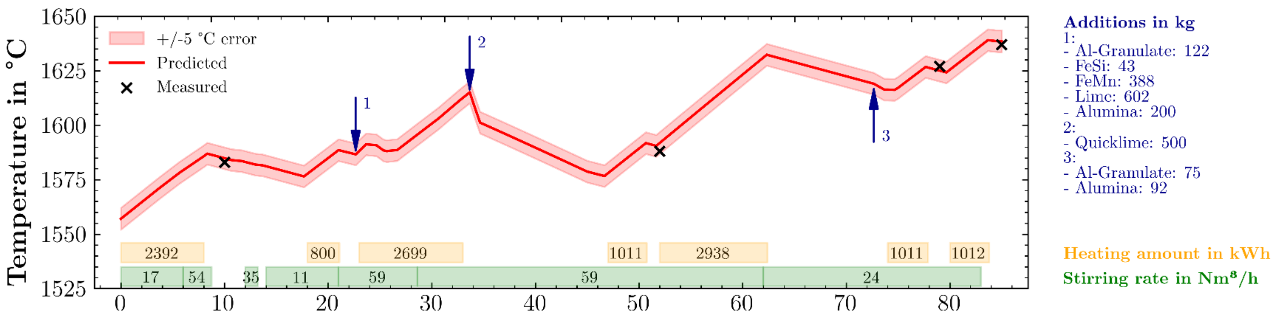




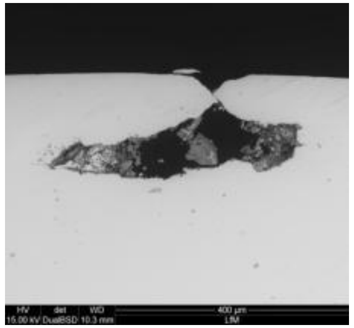
Daniel Kavić: Potential of a hybrid through-process approach for adaptive quality control in ladle treatment of steel: Scientific Exchange Day 2025 (TOMORROW!)

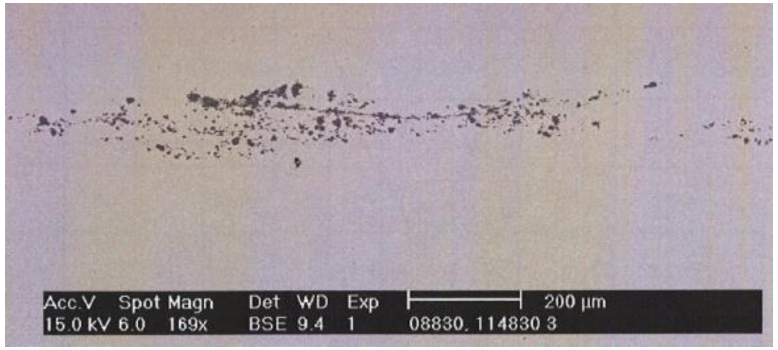
Steel Cleanness

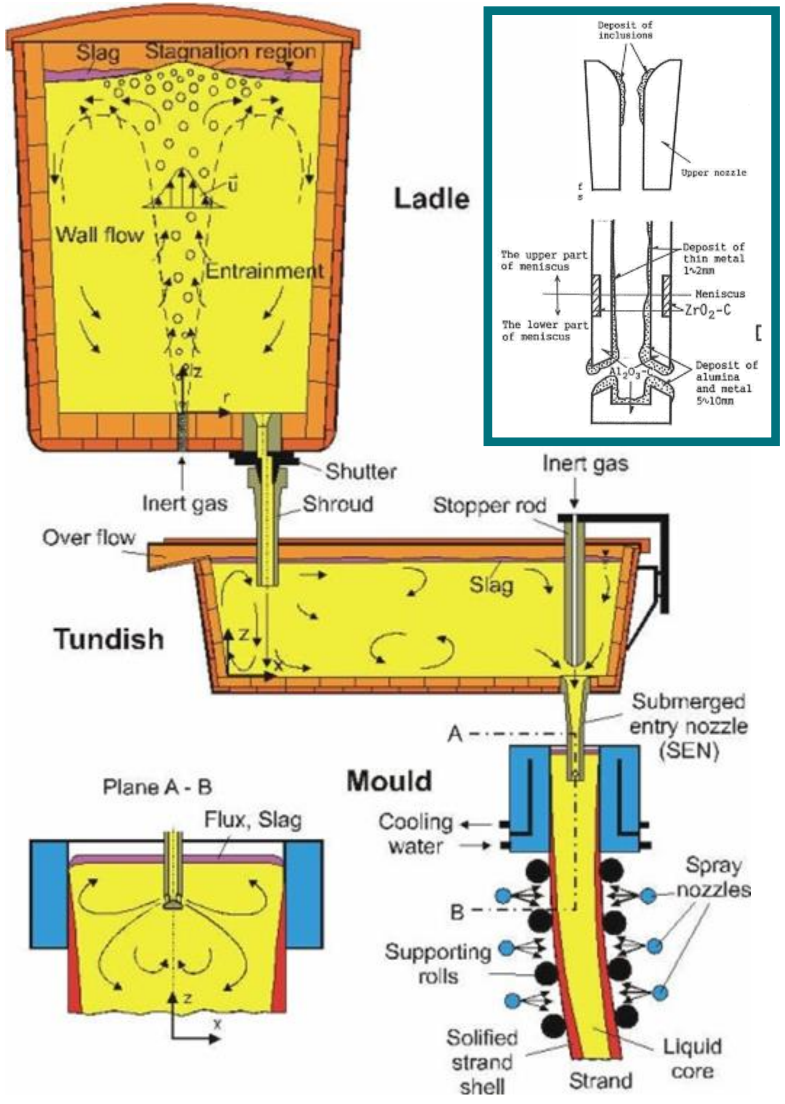
- „Macro-inclusions“
  - Entrapped slags
  - Lining, Sands
  - „Clogging“

  - Inhomogeneous distribution

Defects due to entrapped slag or inclusions



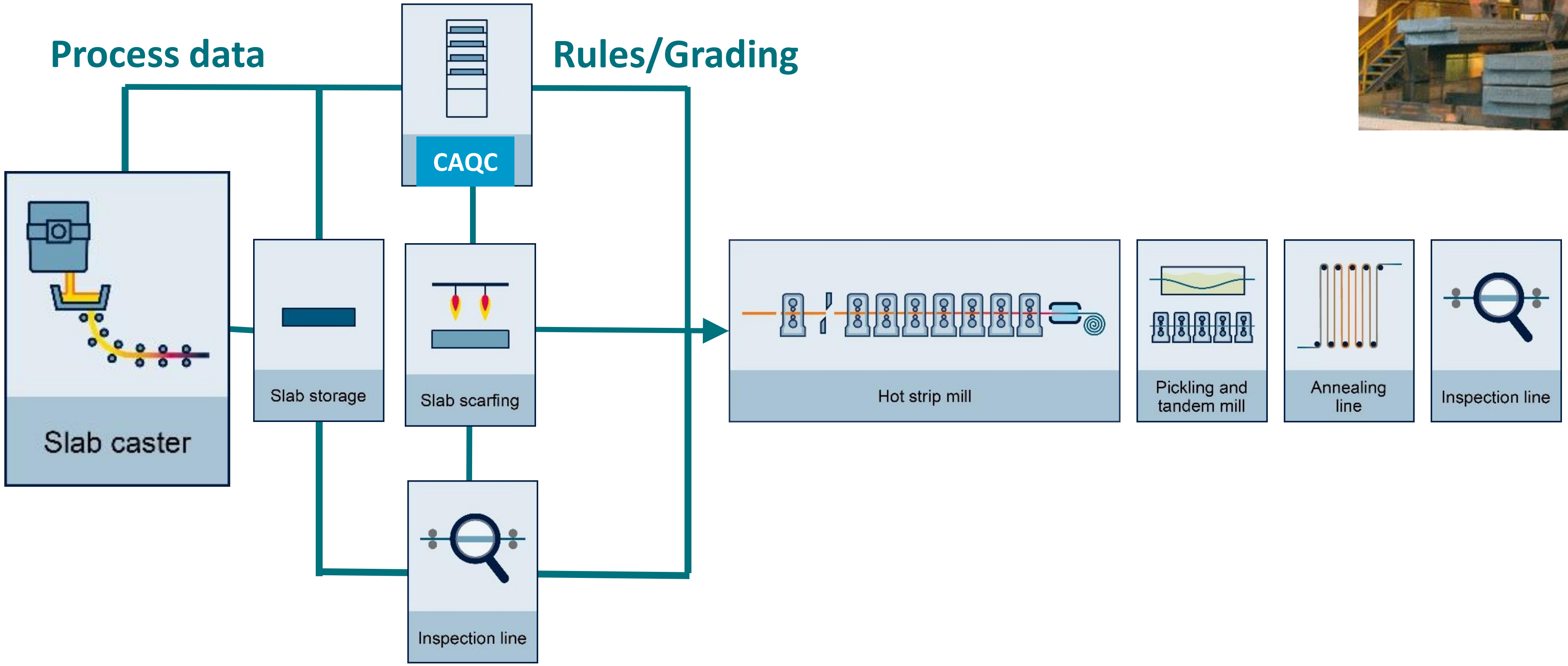


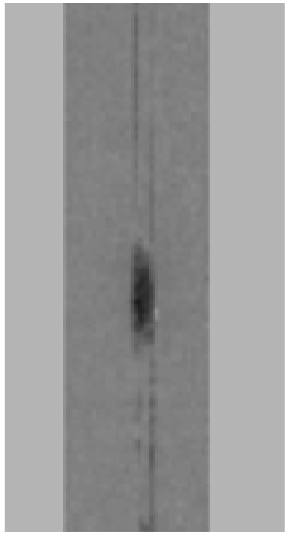


Quelle: Ogibayashi, S. Mechanism and Countermeasure of Alumina Buildup on Submerged Nozzle in Continuous Casting, Taikabutsu Overseas Vol. 15, 1 (1995), S3–14., Bernhard et al.: ECCC 2011 and Master-thesis P. Roppl, MUL 2008

Quality controls vs. quality prediction for casting defects

- **Example surface defects**: To **prevent expensive defects on the product**: **Scarfing of slabs** according to pre-defined rules related to **process parameters** and/or for **critical steel grades**.

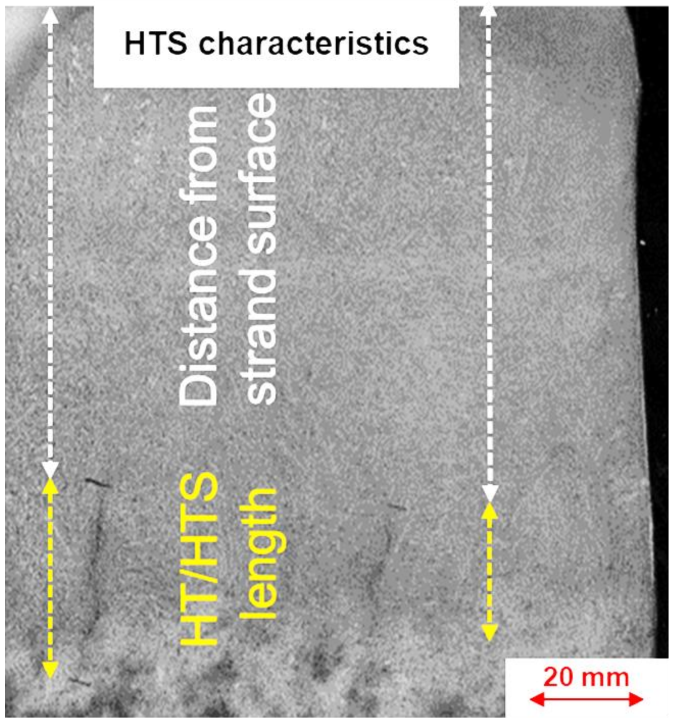




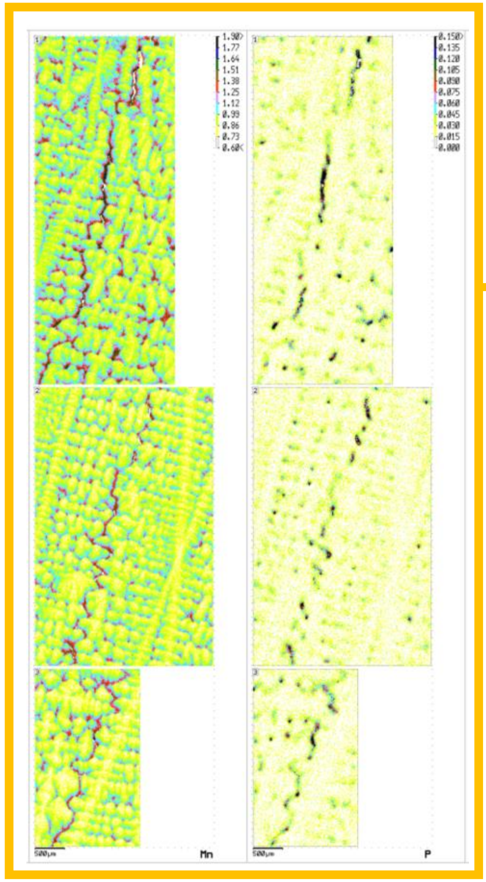
New ways of quality prediction – „hybrid appproach“

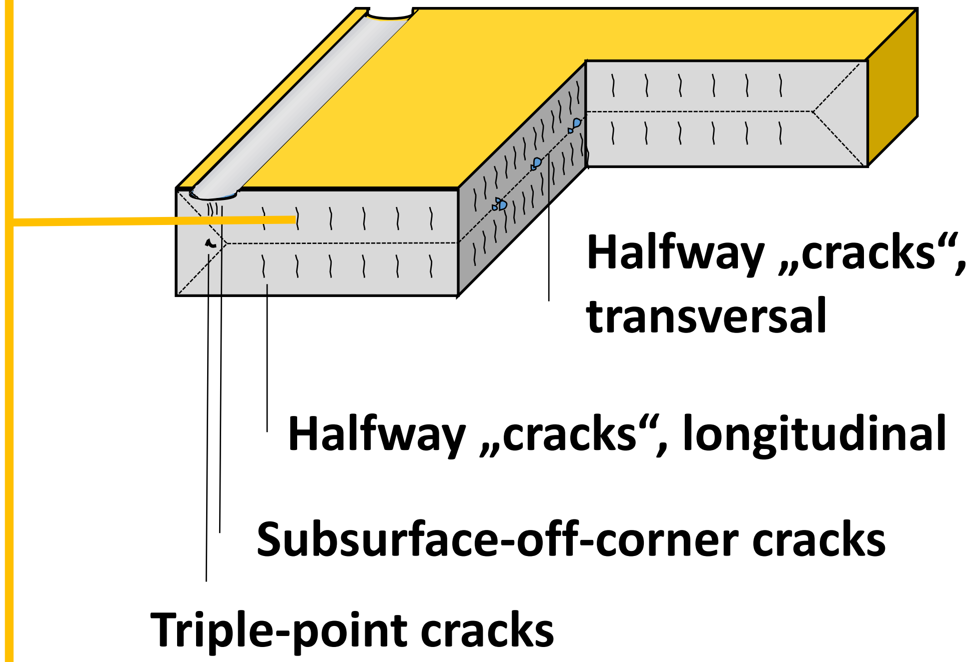
Prediction of internal defects: Hot tearing

- **Appearance of „Hot tears“ in a slab.**



Bernhard, M. Investigations on hot tearing in a continuous slab caster: Numerical modelling combined with analysis of plant results. ECCC 2021.

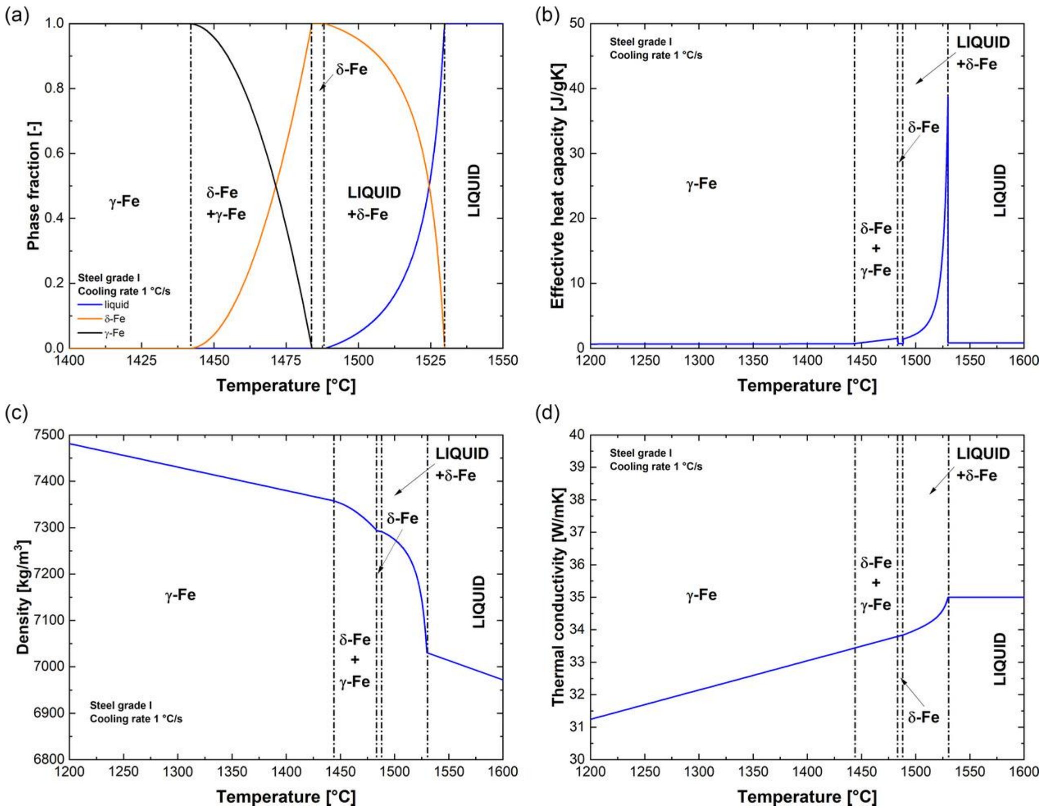


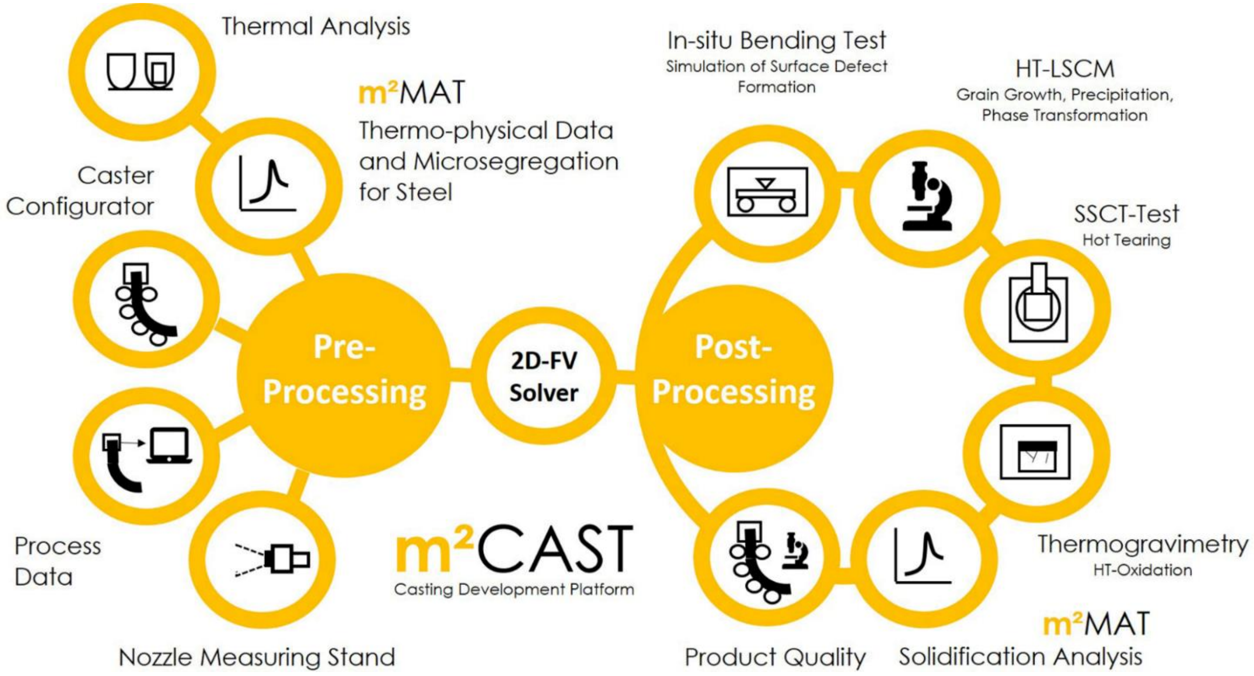


Ilie, S.; Reiter, J.; Fluch, W.; Presslinger, H.; and C. Bernhard: 6th European Continuous Casting Conference, June 4-6 2008, Riccione, Italy, S. Paper – 122

Prediction of internal defects: Hot tearing

- Tools needed to predict hot tearing: white box, grey box, black box.





M. Bernhard et al., steel research international (2022), doi:10.1002/srin.202200089

Prediction of internal defects: Hot tearing

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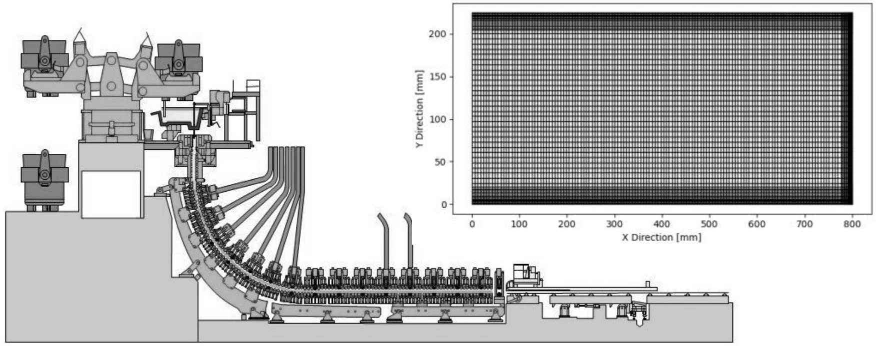
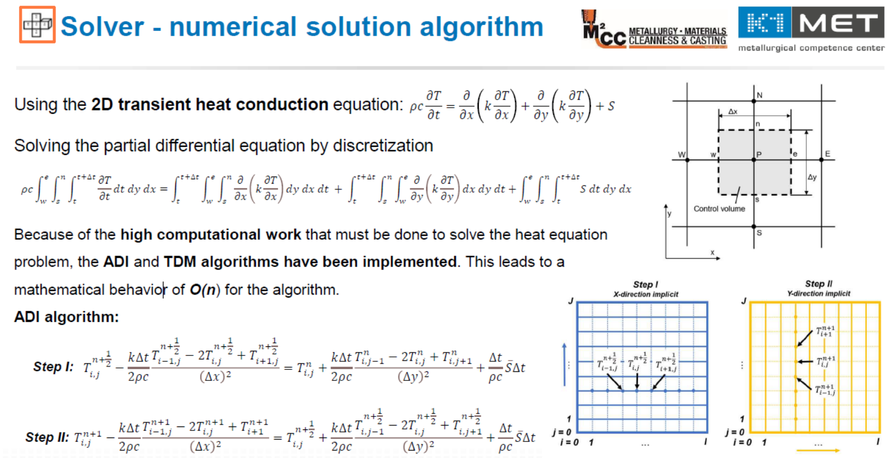
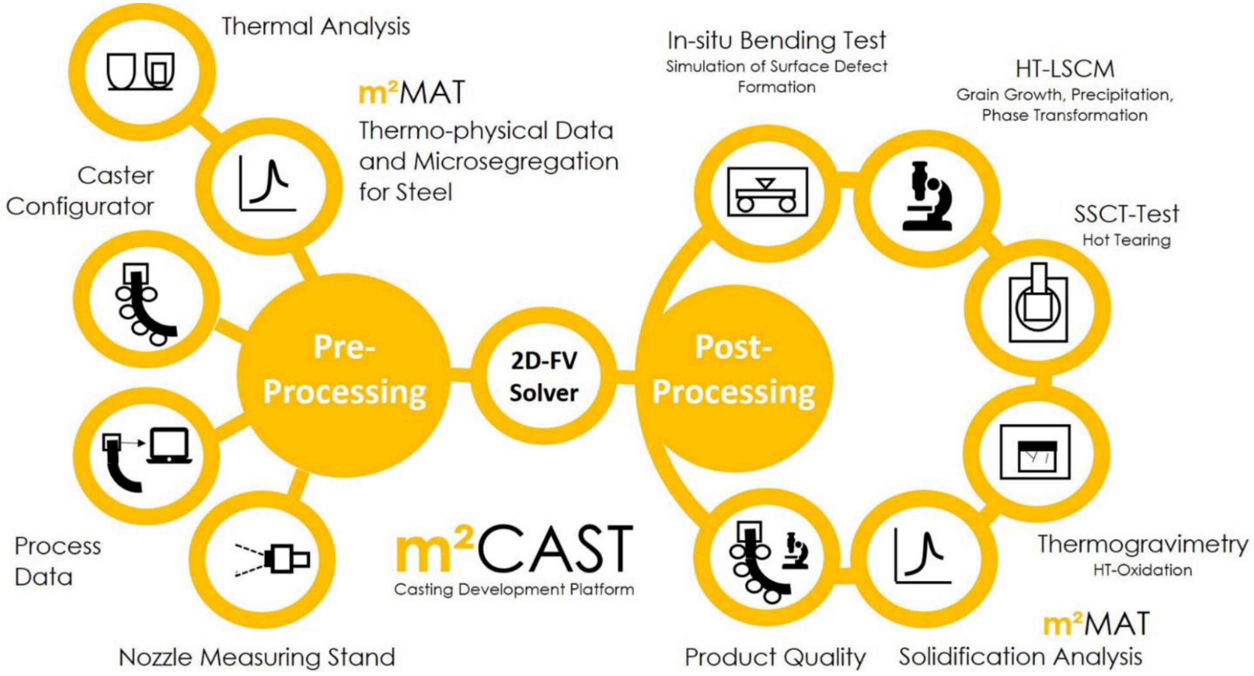




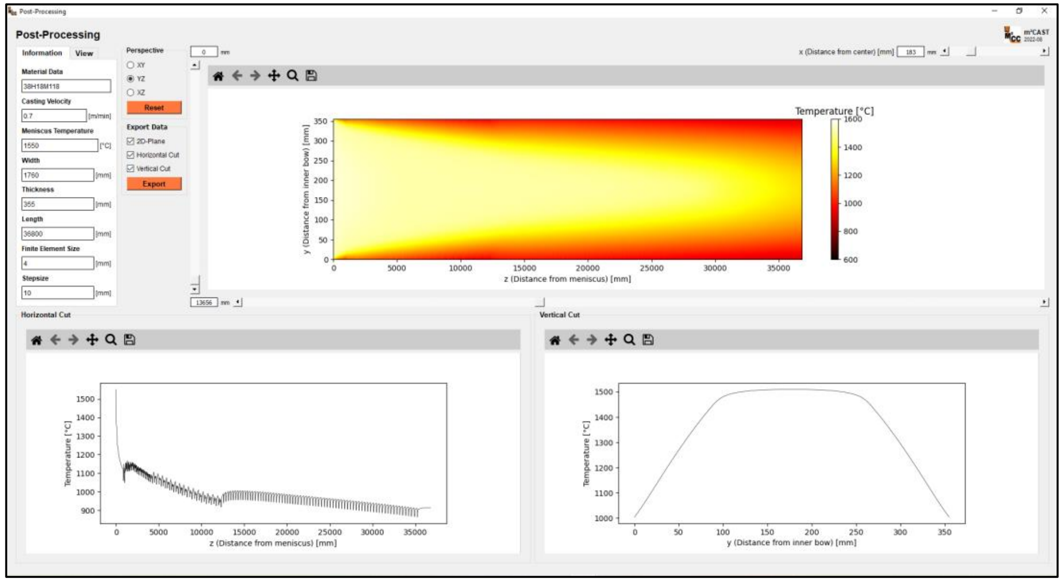
D. Kavić, M. Bernhard, G. Wieser, M. Taferner, S. Ilie and C. Bernhard: A 2D – finite volume solidification software for real-time simulation of continuous slab casting, ECCC 2024.

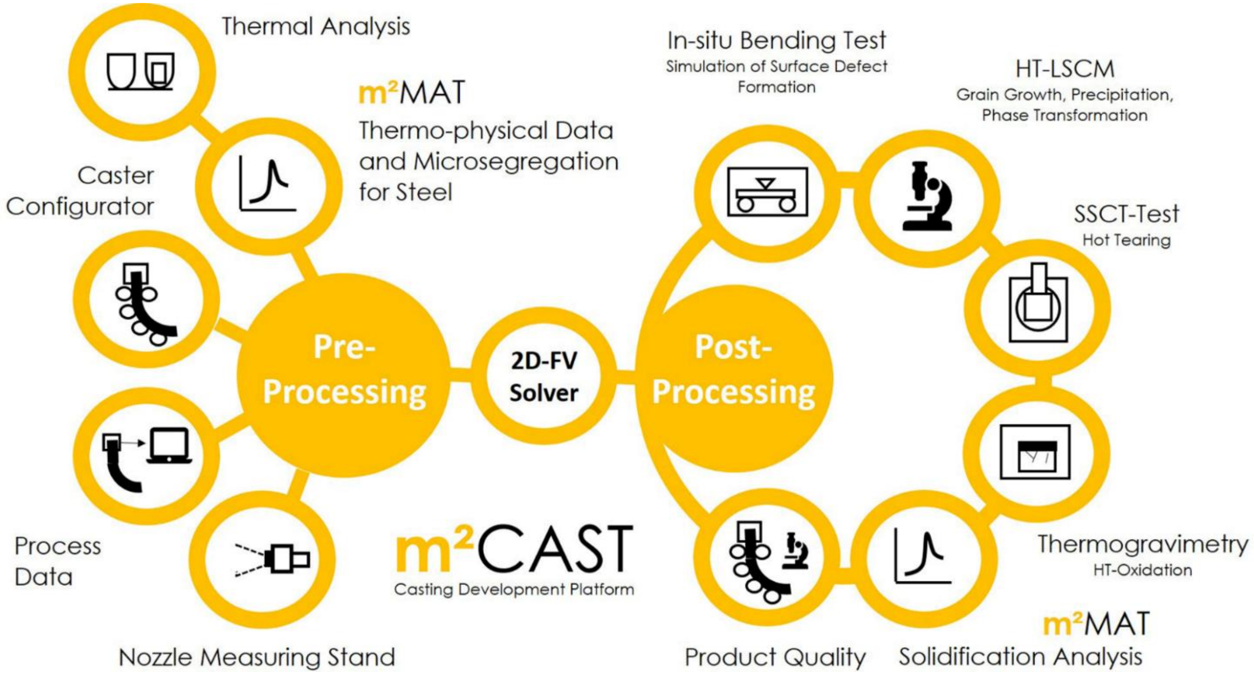


M. Bernhard et al., steel research international (2022), doi:10.1002/srin.202200089

Prediction of internal defects: Hot tearing

- **Tools needed to predict hot tearing: white box, grey box, black box.**
- Advantage: Low CPU time, high resolution.
- Phase transformation kinetics, microstructure evolution, strain analysis, defect prediction functions.





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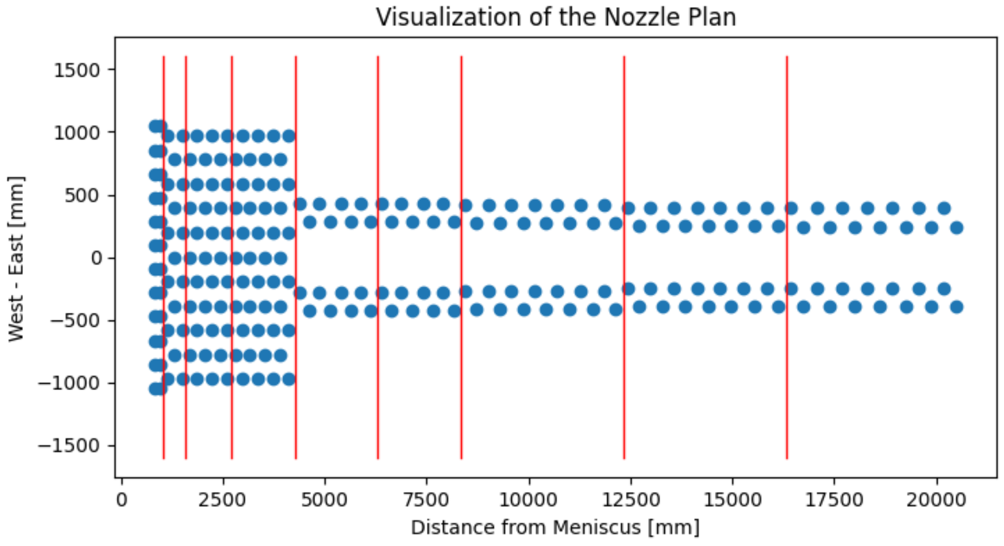
Prediction of internal defects: Hot tearing

- **Tools needed to predict hot tearing: white box, grey box, black box.**
- Local HTC as a function of surface temperature, local WID, water and air pressure, water flow rate, position (statistical modelling).



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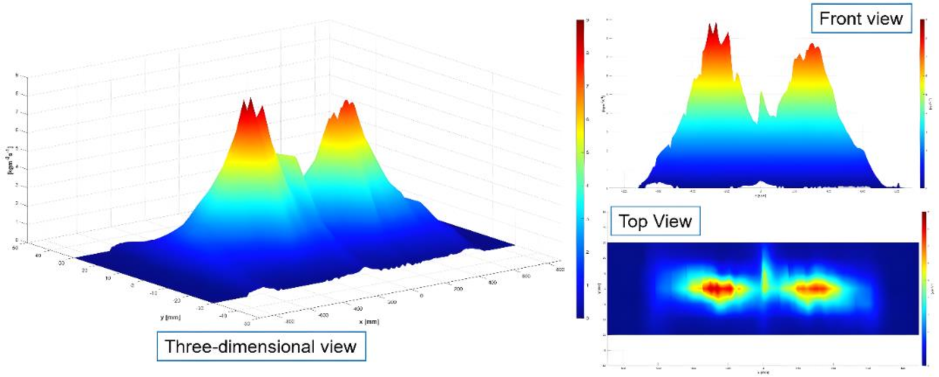
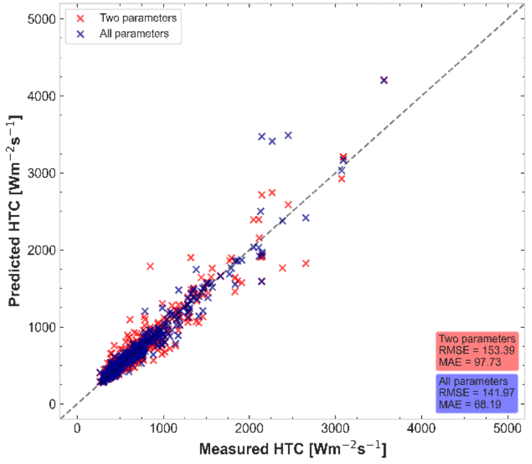
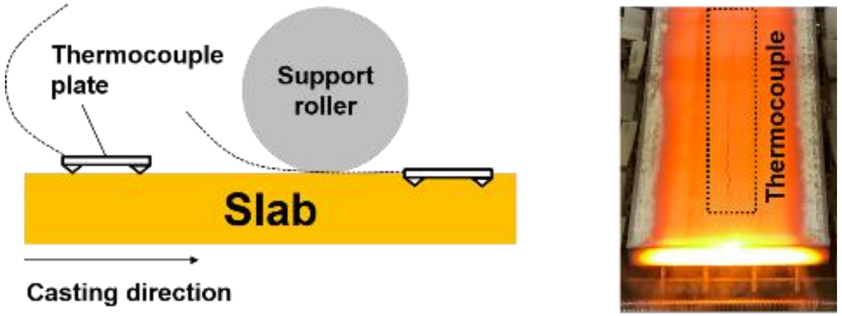
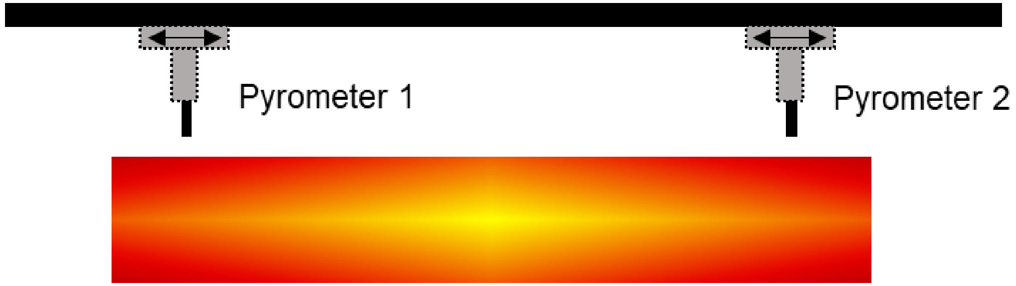




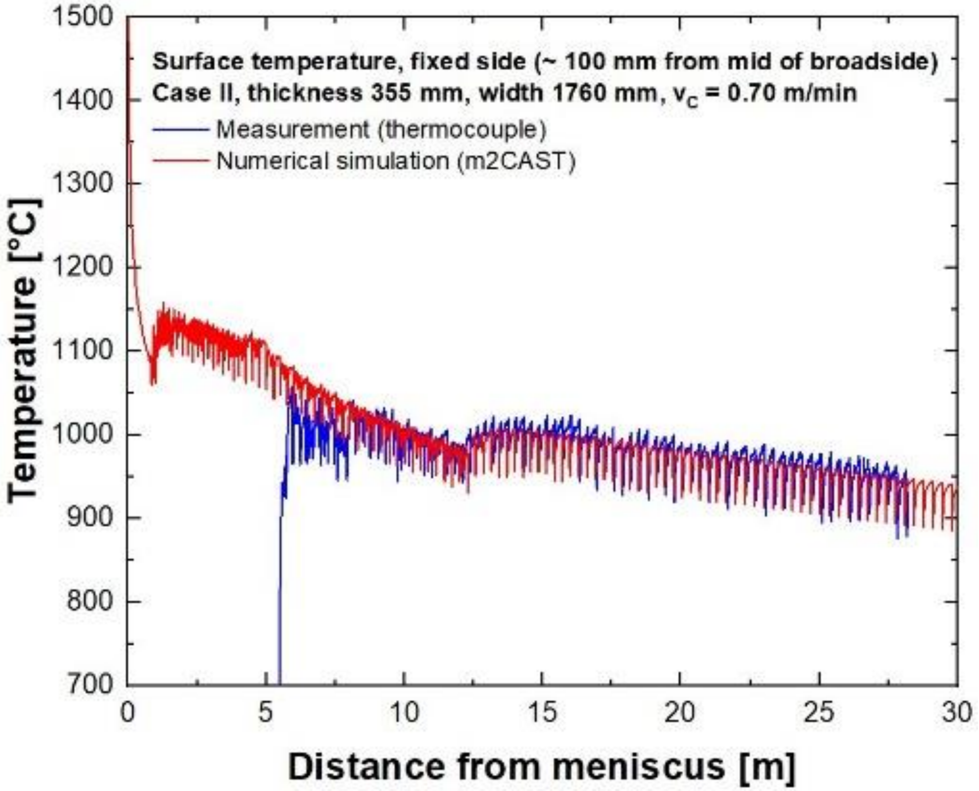
M. Seidl, D. Kavić, S. Ilie, C. Bernhard: Hybrid solution for local heat transfer coefficients in a transient solidification model for continuous casting, BHM 2025.

- **Tools needed to predict hot tearing: white box, grey box, black box.**
- Parametrization by means of measurement.





G. Santos et al, *9th Int. Conf. on Modeling and Simulation of Metallurgical Processes in Steelmaking*, Vienna, Austria 2021.



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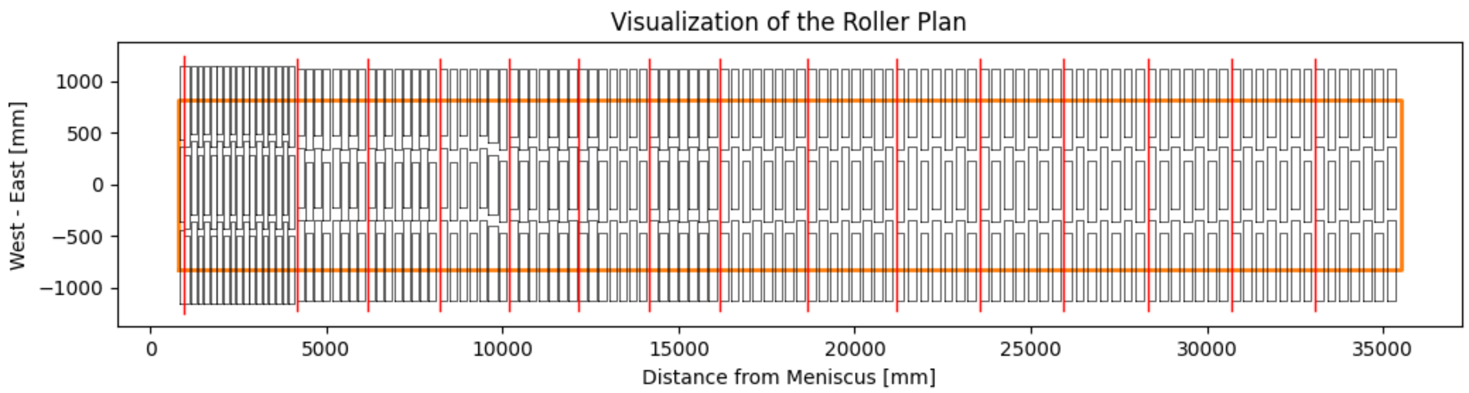
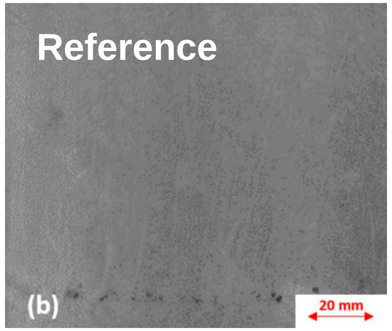
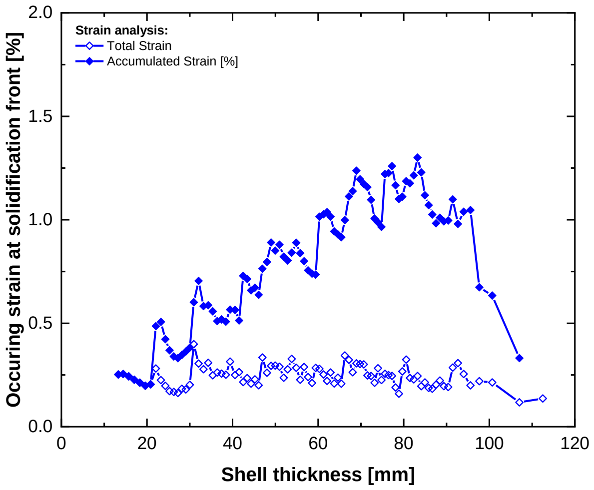
Prediction of internal defects: Hot tearing

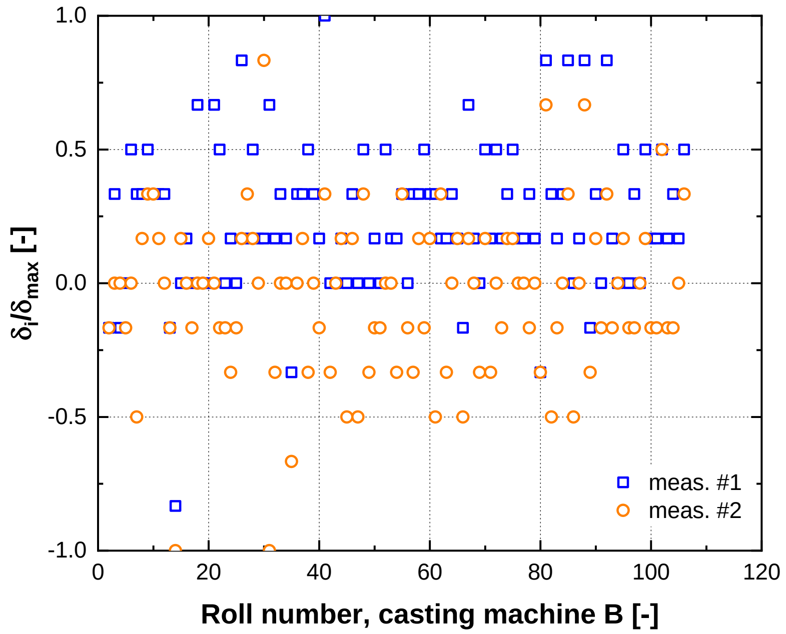
- **Tools needed to predict hot tearing: Maintenance, strain analysis.**



$$\varepsilon_{acc} = \int_{t_{SA}} \dot{\varepsilon} dt; \ t_{SA} = \frac{\Delta T_{SA}}{\dot{T}}$$







Bernhard, M. Investigations on hot tearing in a continuous slab caster: Numerical modelling combined with analysis of plant results. ECCC 2021.

Prediction of internal defects: Hot tearing

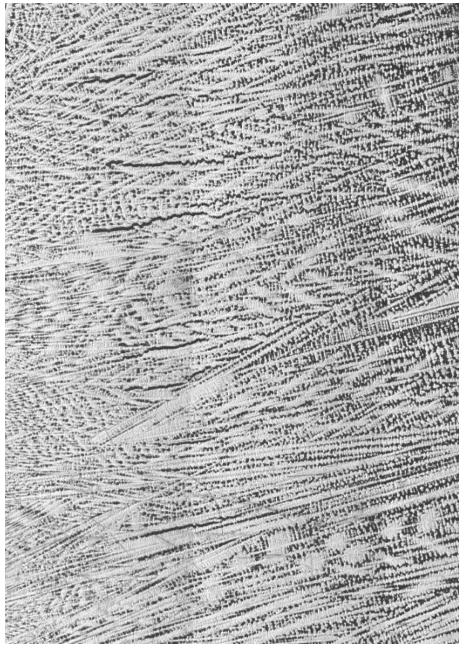
- **Phenomenological quality prediction function**

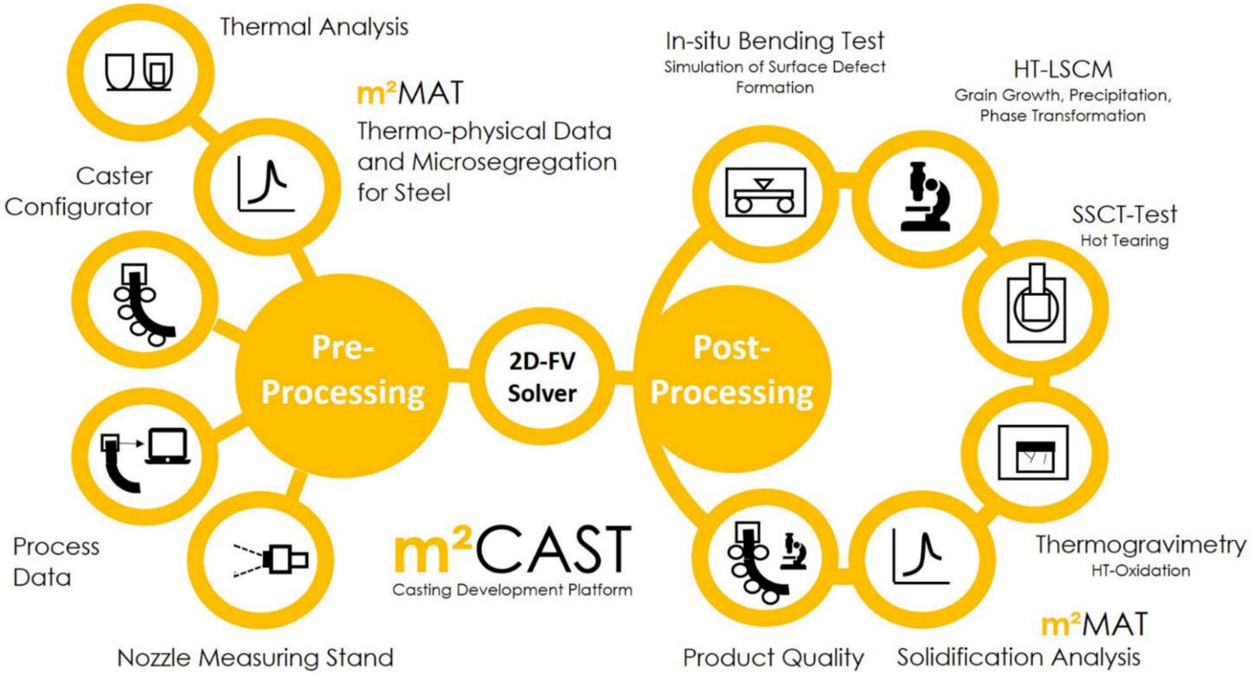
  $\varepsilon_{acc} > \varepsilon_{critical}$

- $\varepsilon_{critical}$ **from Won (1998, 2000) criterion.**

$$\varepsilon_c = \frac{\varphi}{\dot{\varepsilon}^{m^*} \Delta T_B^{n^*}}$$

- $\varepsilon_{critical}$ **from experiment (SSCT-test): ≈ 1.2 %.**





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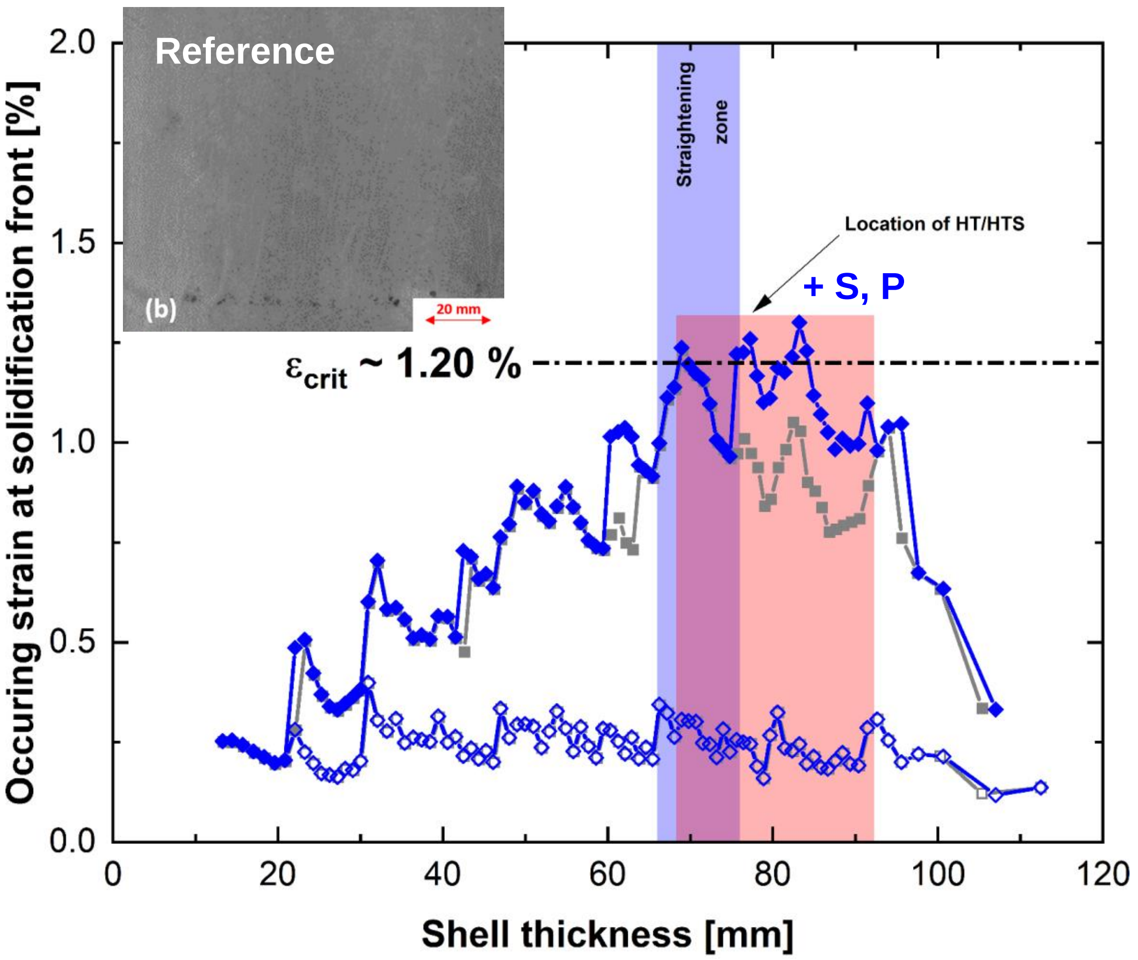
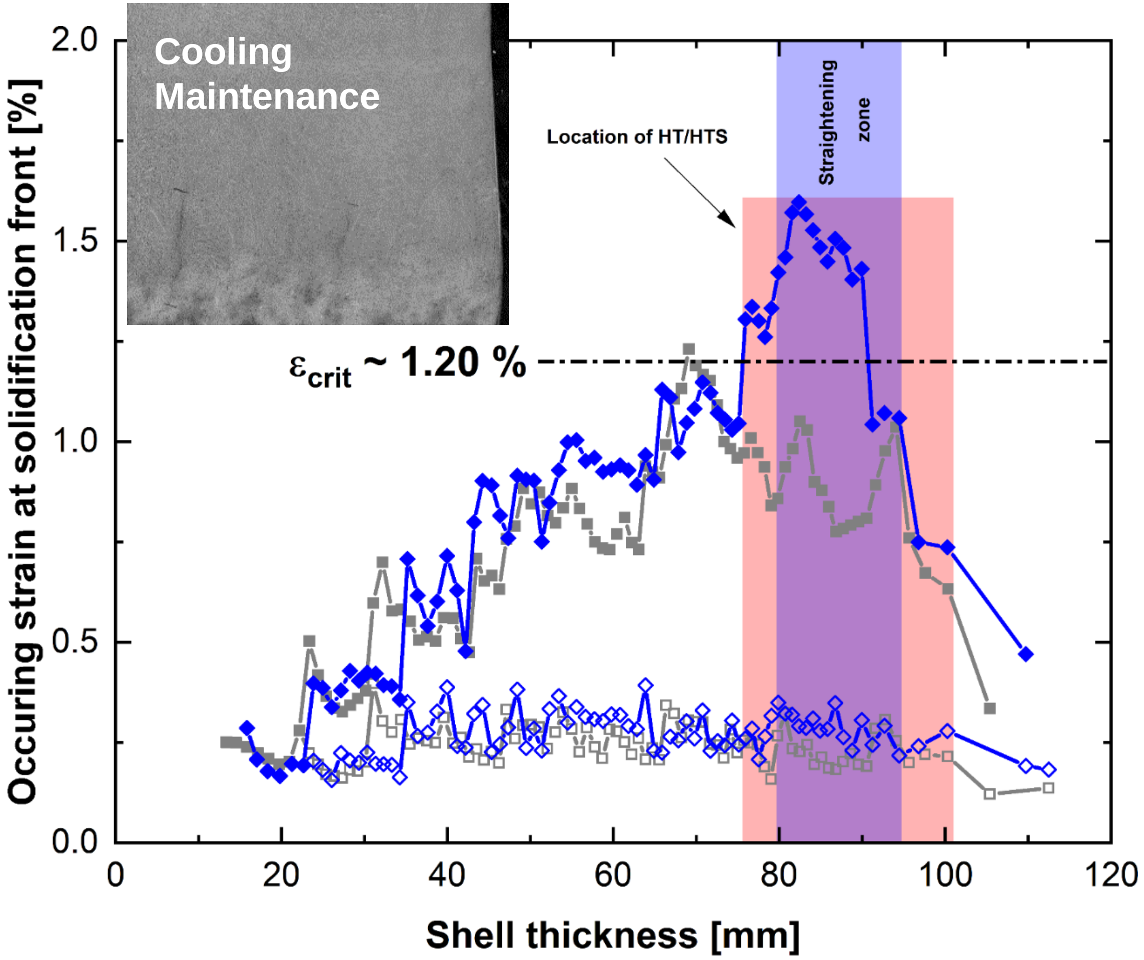
Prediction of internal defects: Hot tearing

Bernhard, M. Investigations on hot tearing in a continuous slab caster: Numerical modelling combined with analysis of plant results. ECCC 2021.

- **Influencing parameters: Steel composition, cooling table, maintenance.**





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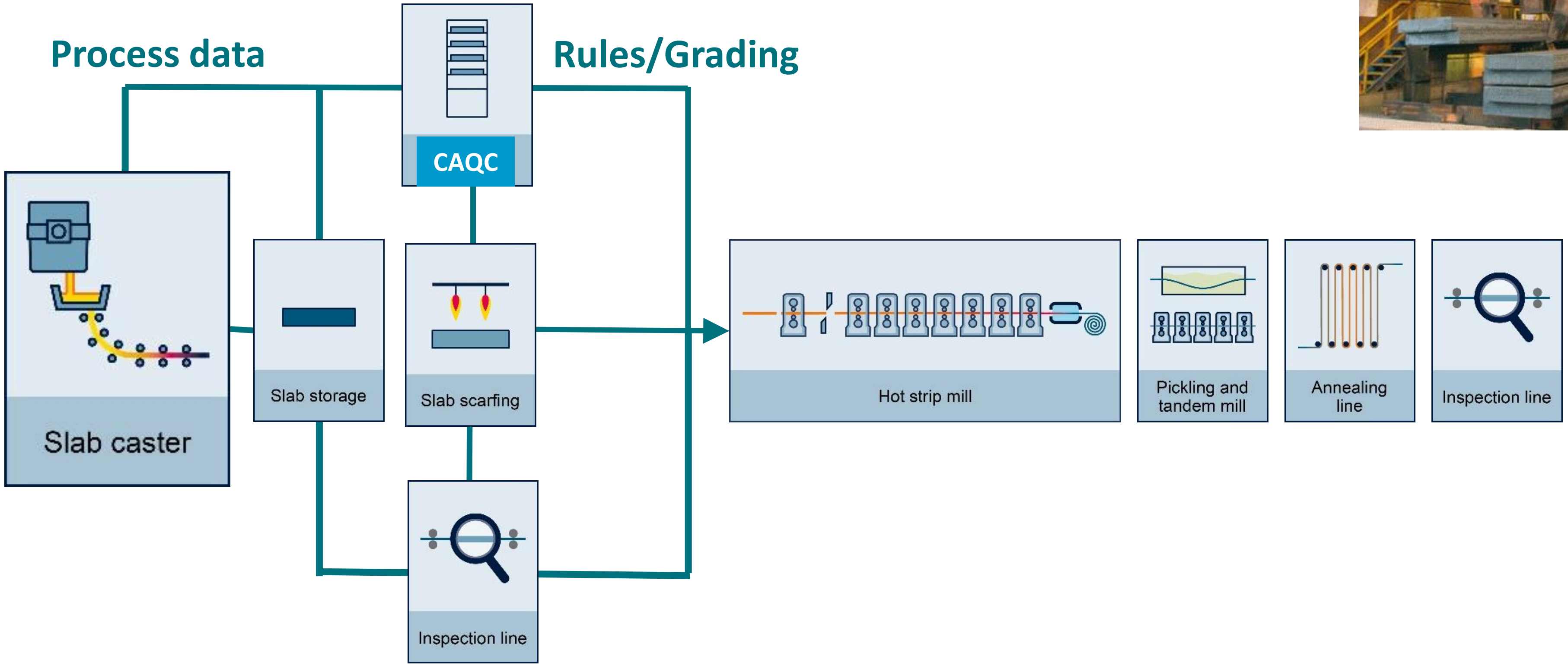
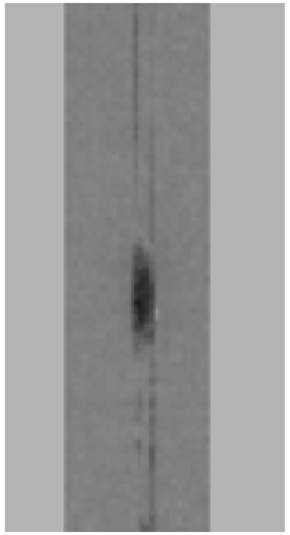
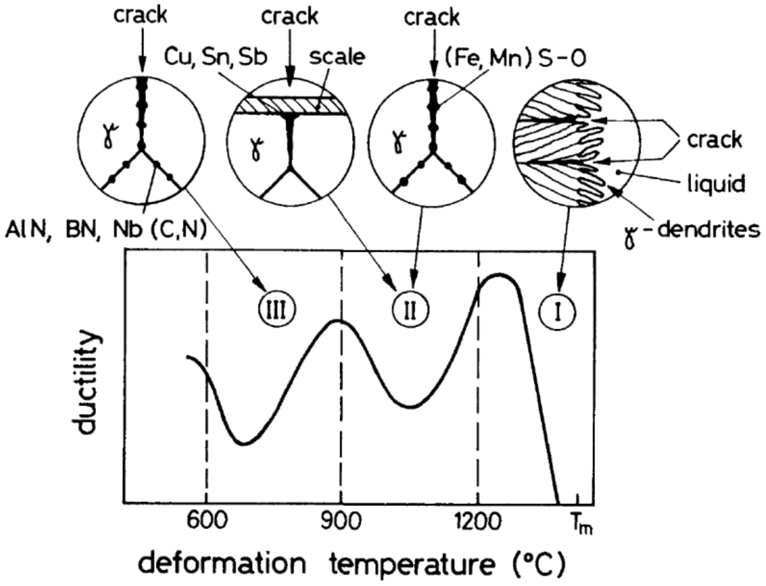


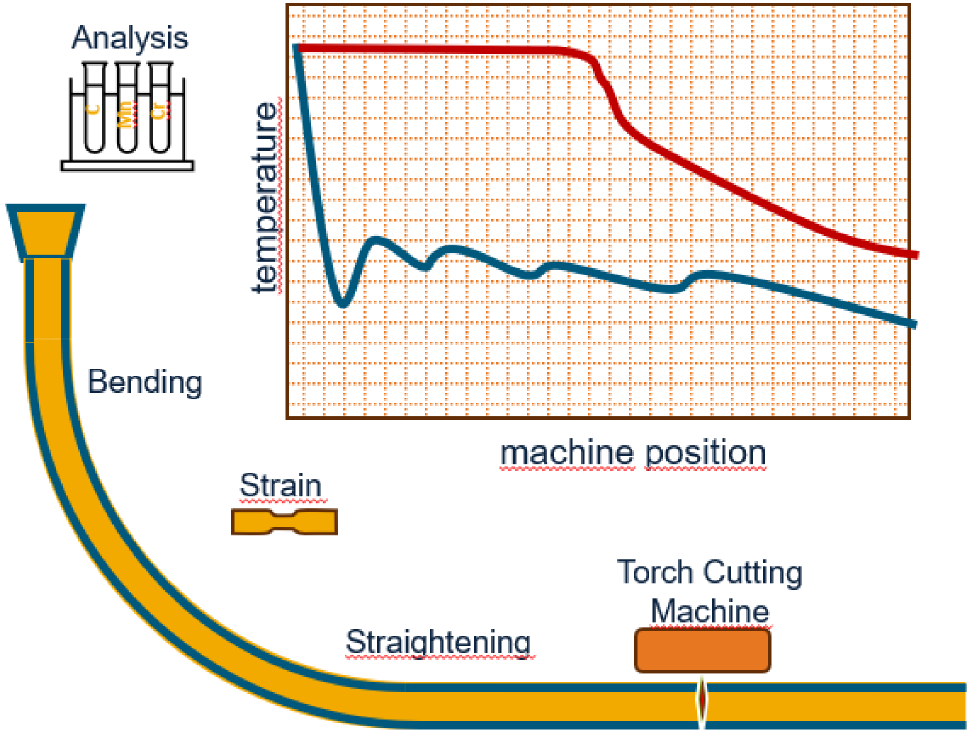


New ways of quality prediction – „hybrid appproach“

Surface Quality Prediction

- **A simple quality prediction function.**





Wolf, M.M., Fine Intergranular Surface Crack in Bloom Casting, Trans. ISIJ, Vol. 24, 1984, 351-358.

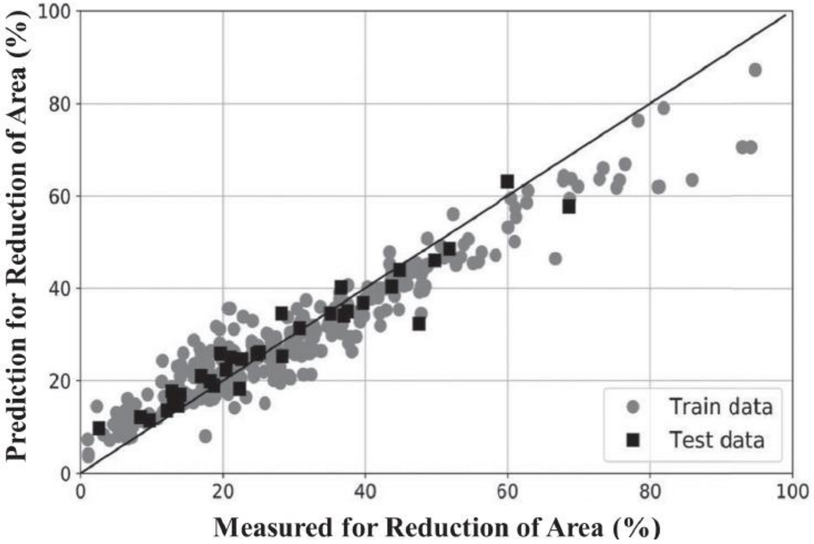
Surface Quality Prediction

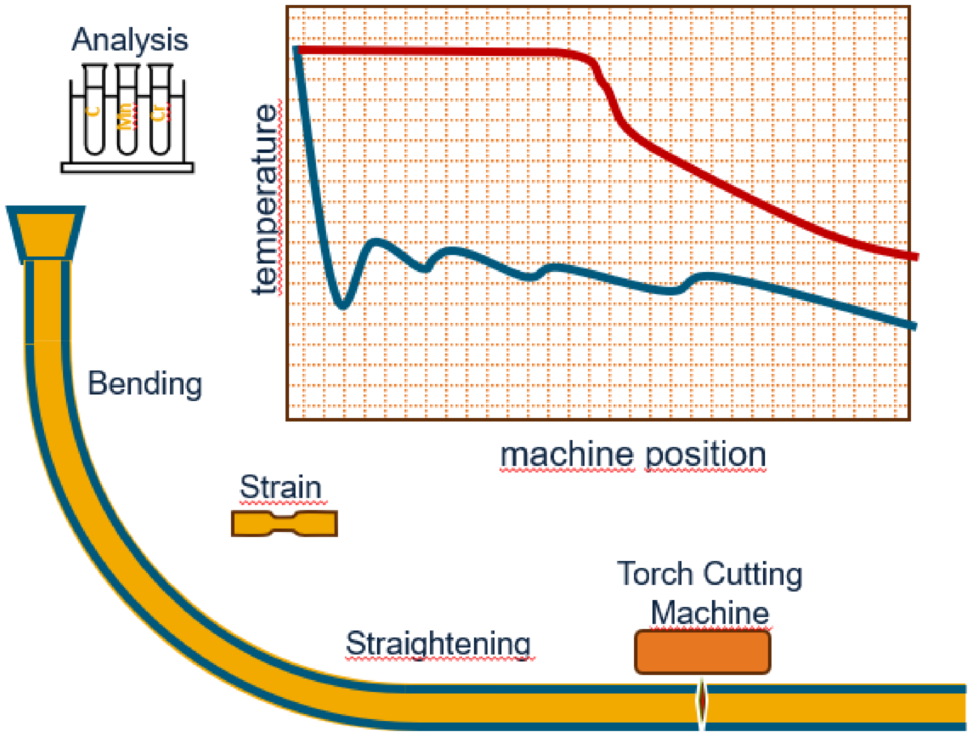
- **A simple quality prediction function.**

Article

Deep Learning to Predict Deterioration Region of Hot Ductility in High-Mn Steel by Using the Relationship between RA Behavior and Time-Temperature-Precipitation

Ji-Yeon Jeong [1,2], Dae-Geun Hong [2,*] and Chang-Hee Yim [2,*]



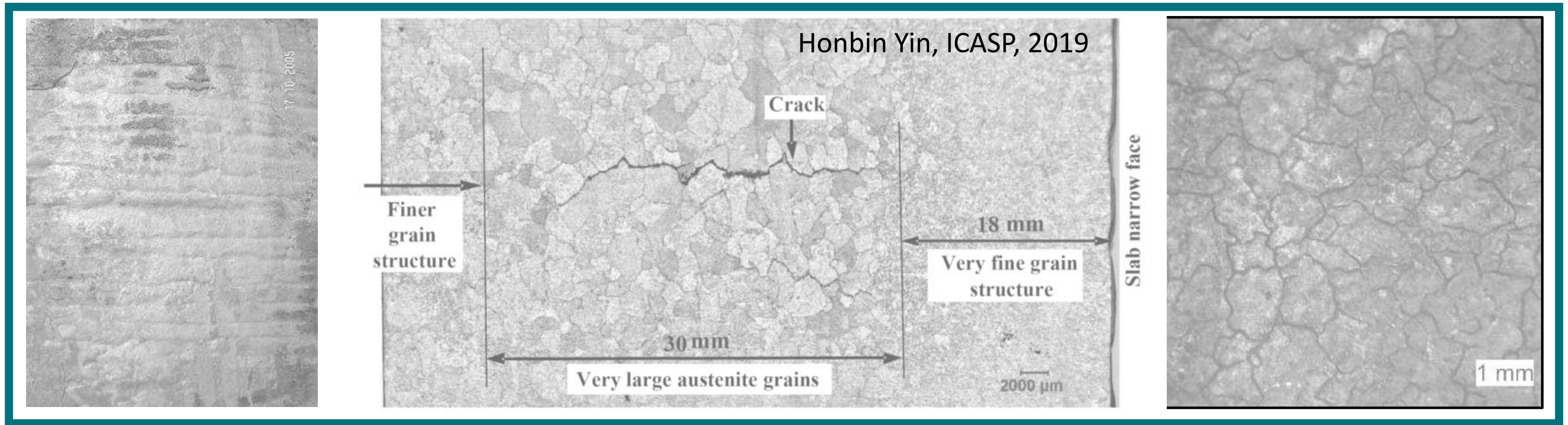


Sang-Hum Kwon, Dae-Geun Hong & Chang-Hee Yim, Prediction of hot ductility of steels from elemental composition and thermal history by deep neural networks, Ironmaking & Steelmaking, 47 (2020), 1176-1187, DOI: 10.1080/03019233.2019.1699358

Surface Quality Prediction

- **Root causes fine cracks:**
  - Surface depressions
  - Oscillation marks
  - Coarse austenite grains
  - Residuals, **tramp elements**

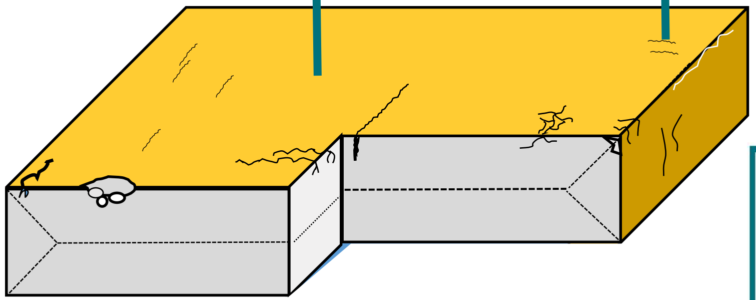
Defects forming due to surface depressions and grain boundary oxidation

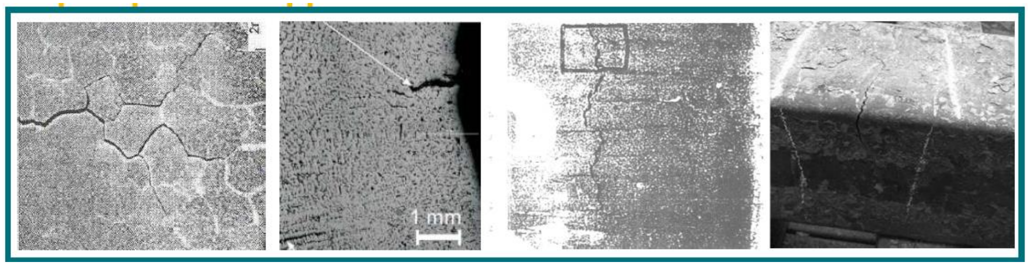


Deep oscillation marks and surface depressions

Longitudinal off-corner depression („Gutter“) with transverse cracks

Network cracks in deep OM (billet)





Melford, D.A., J. Iron Steel Inst. 204 (1966); Salter, W. J. M. j. Iron Steel Inst. 204 (1966)

Phenomenological quality criteria (quality indices)

$$QI_{SHE} = \max_{T_{SOL-30°C} \le T < T_{SOL}} (f_\delta(T_{SOL}) - f_\delta(T)) \quad (1)$$

$$QI_{STR} = \max_{T_{SOL} \le T < T_{ZST}} (f_\delta(T_{ZST}) - f_\delta(T)) \quad (2)$$

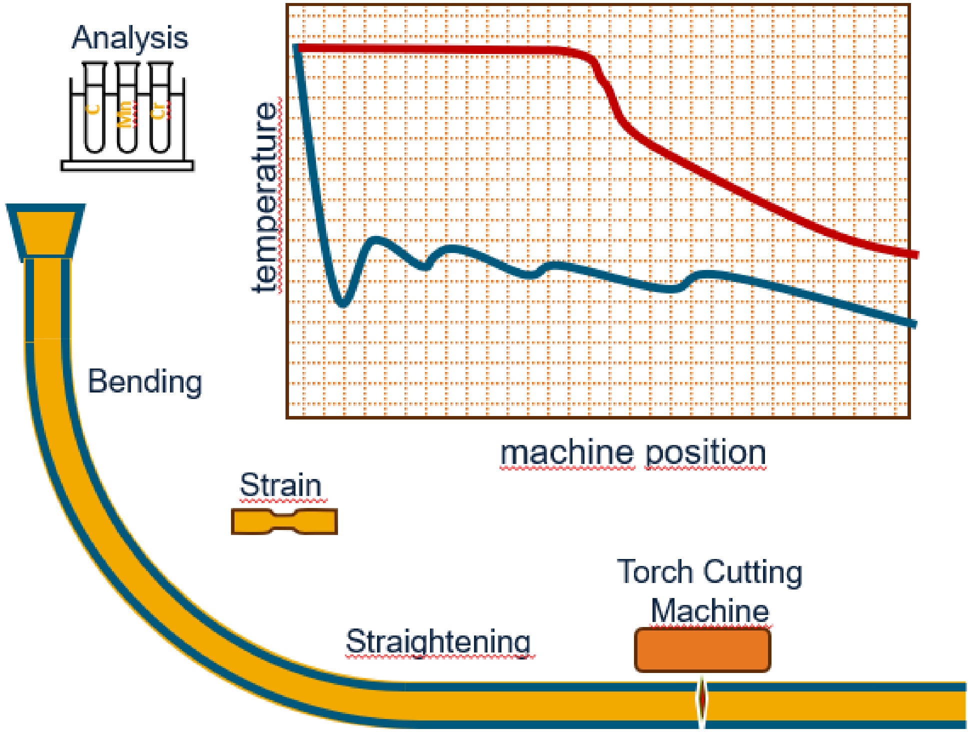
$$QI_{AUS} = \begin{cases} (f_\gamma(T_{SOL}) - f_\gamma(T_{FER-})), & \text{if} \quad T_{SOL} < T_{FER-} \le T_{ZST} \\ (f_\gamma(T_{SOL}) - f_\gamma(T_{ZST})), & \text{if} \quad T_{FER-} > T_{ZST} \\ 0, & \text{if} \quad T_{FER-} \le T_{SOL} \end{cases} \quad (3)$$

$$QI_{SHE+STR+AUS} = QI_{SHE} + QI_{STR} + QI_{AUS} \quad (4)$$

$$QI_{SOL} = f(x_i(T_{SOL}), f(\mathrm{Mn, Fe})\mathrm{S}), \text{ where } i = \{\mathrm{S, P, B}\} \quad (5)$$

$$QI_{DUC}(T_0, T_1) = f(\gamma_i(T_0) - \gamma_i(T_1)), \text{ where } i = \{(\mathrm{Mn, Fe})\mathrm{S}, \mathrm{AlN}, \mathrm{BN}, (\mathrm{C, N})\mathrm{Nb}, \ldots\} \quad (6)$$

$$QI_{CUMULATIVE} = \frac{\frac{QI_1}{\max(QI_1)} + \frac{QI_2}{\max(QI_2)} + \frac{QI_3}{\max(QI_3)} + \ldots \frac{QI_n}{\max(QI_n)}}{n} \quad (7)$$



Julius Norrena, Seppo Louhenkilpi, Ville-Valtteri Visuri, Tuomas Alatarvas, Agne Bogdanoff, and Timo Fabritius: Assessing the Effects of Steel Composition on Surface Cracks in Continuous Casting with Solidification Simulations and Phenomenological Quality Criteria for Quality Prediction Applications, steel research 2022.

Surface Quality Prediction

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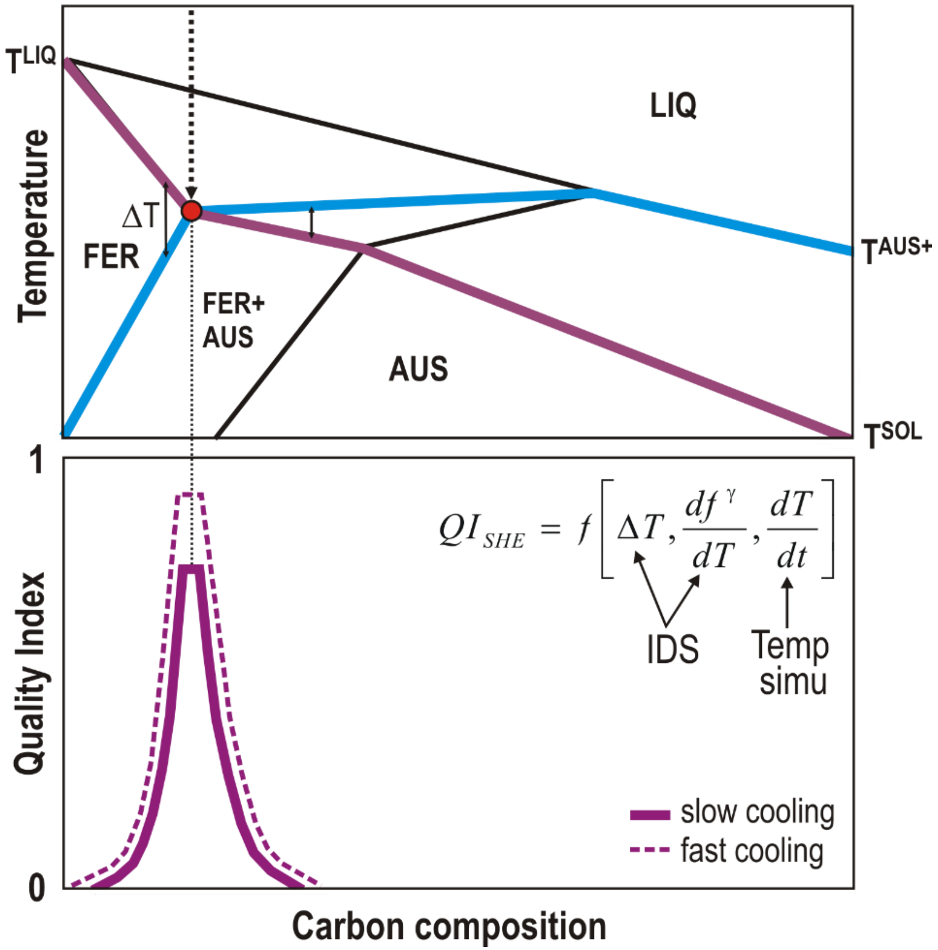
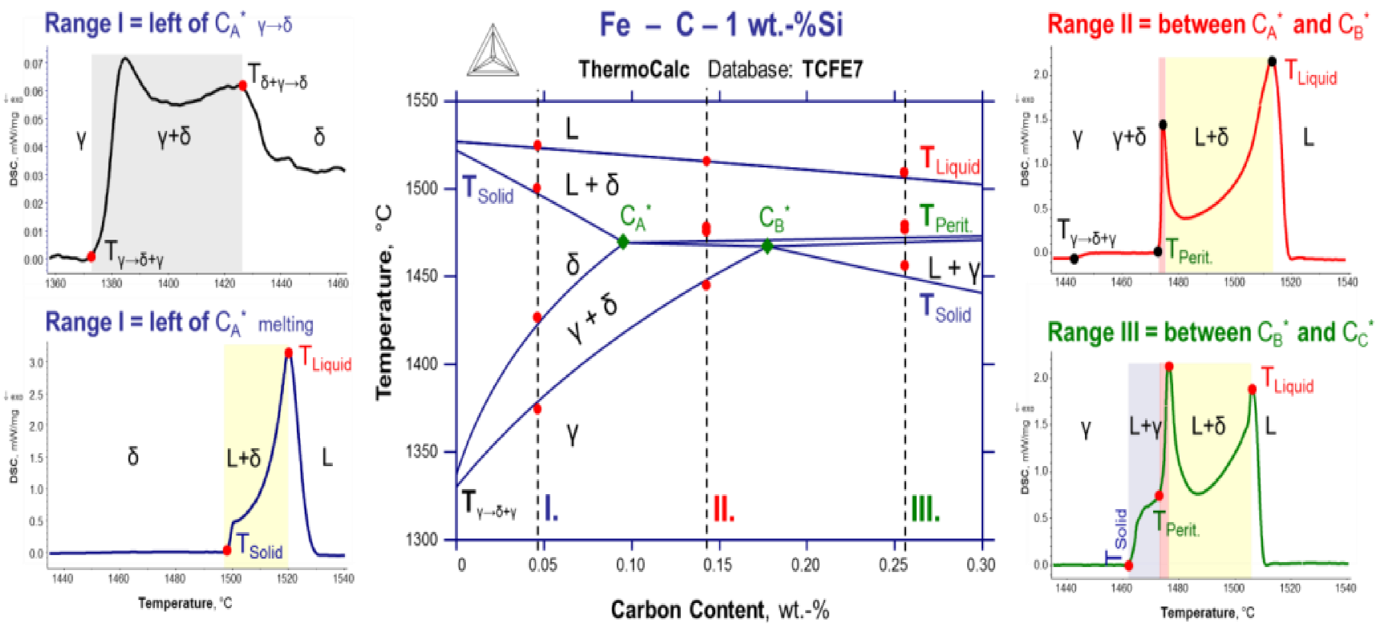


Surface Quality Prediction

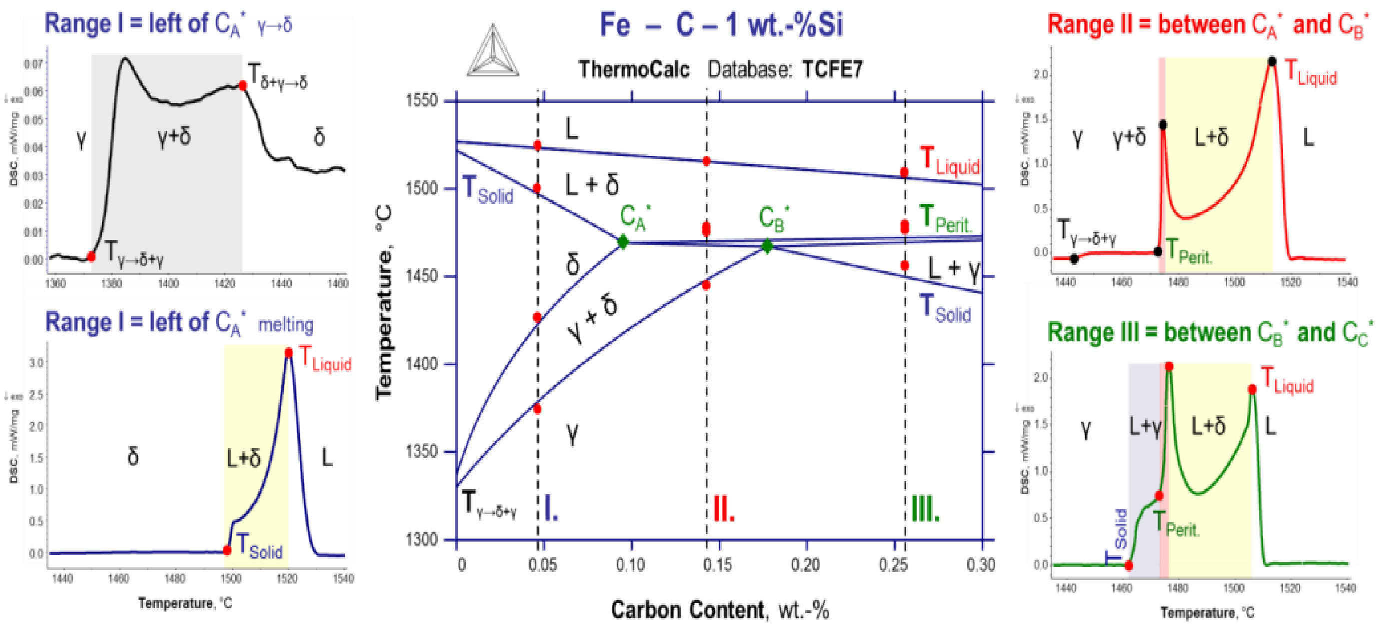
◆ Parametrization: DTA-measurements

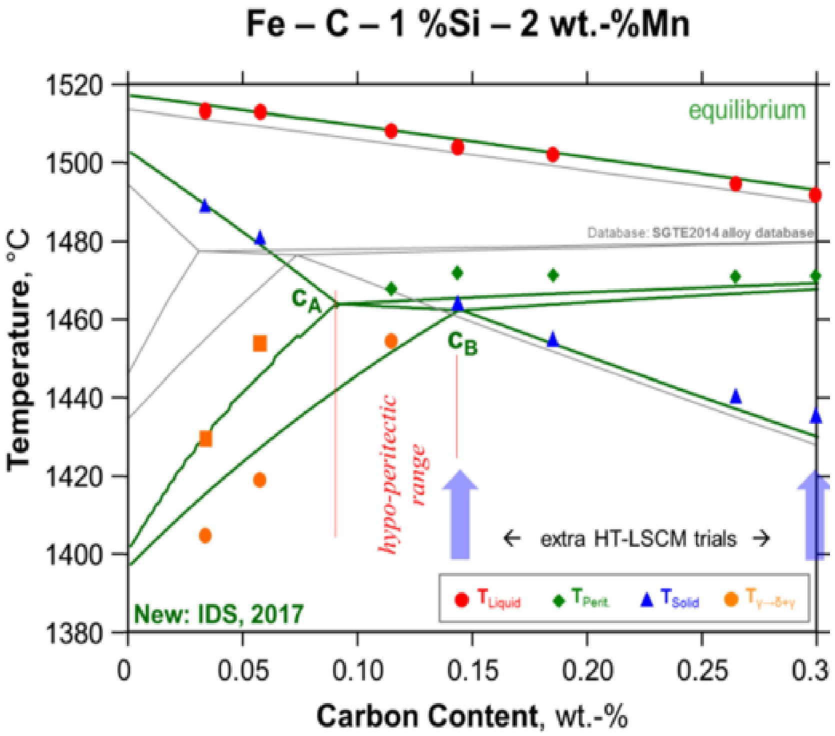


Peter Presoly, Daniel Kavic, Christian Bernhard, Susanne Hahn, Sergiu Ilie: Classification of peritectic steels by experimental methods, computational thermodynamics and plant data: An Overview, ESTAD 2023

Surface Quality Prediction

◆ Parametrization: DTA-measurements





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Surface Quality Prediction

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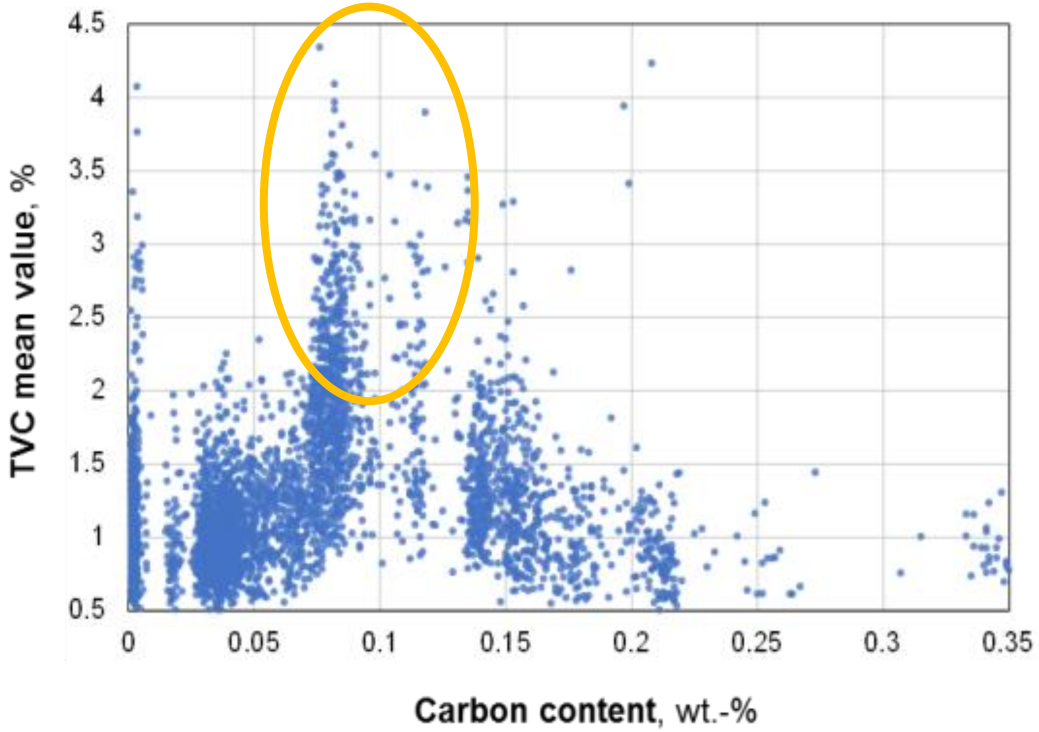

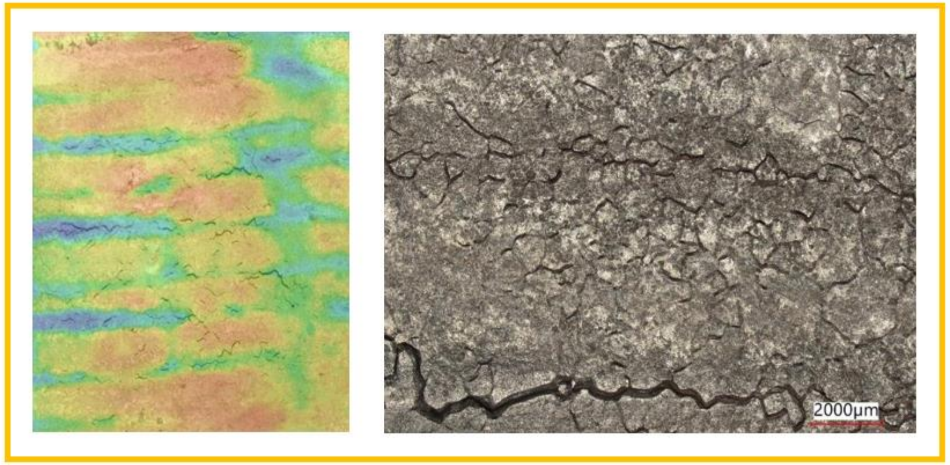

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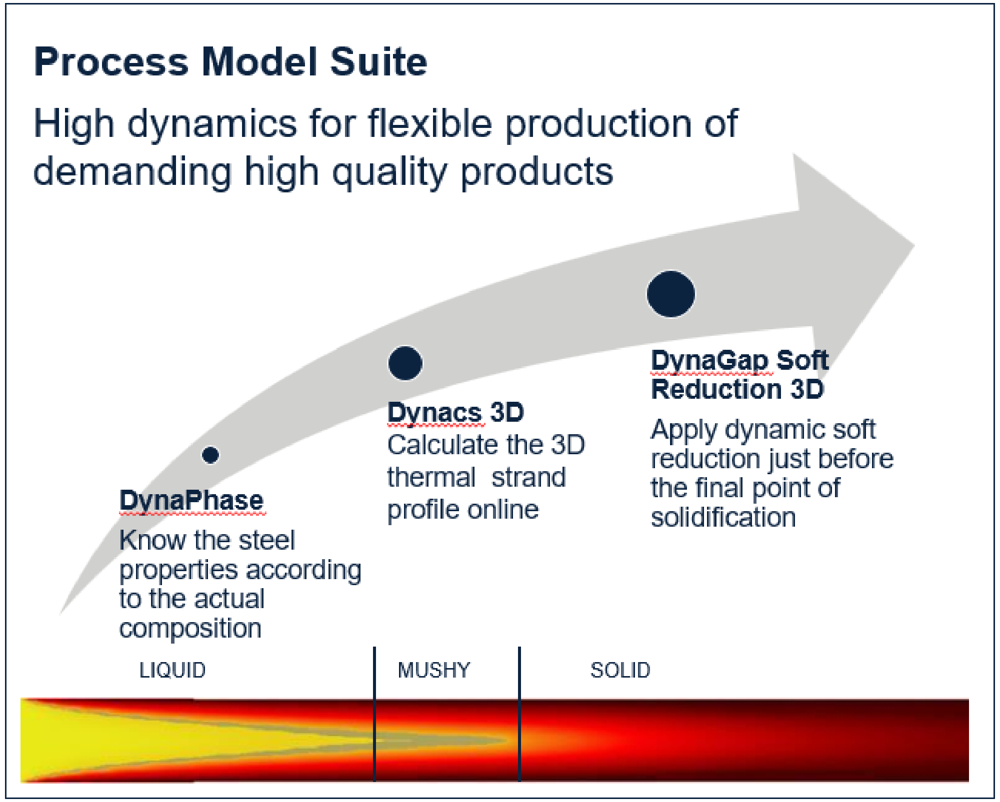
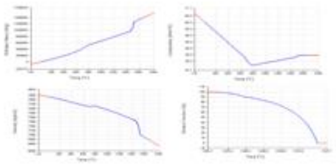
Surface Quality Prediction

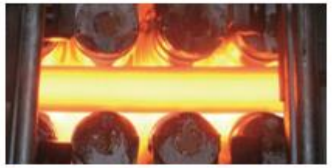
- Online quality prediction: DynaPhase and SQI



Real Plant



Metallurgy & material

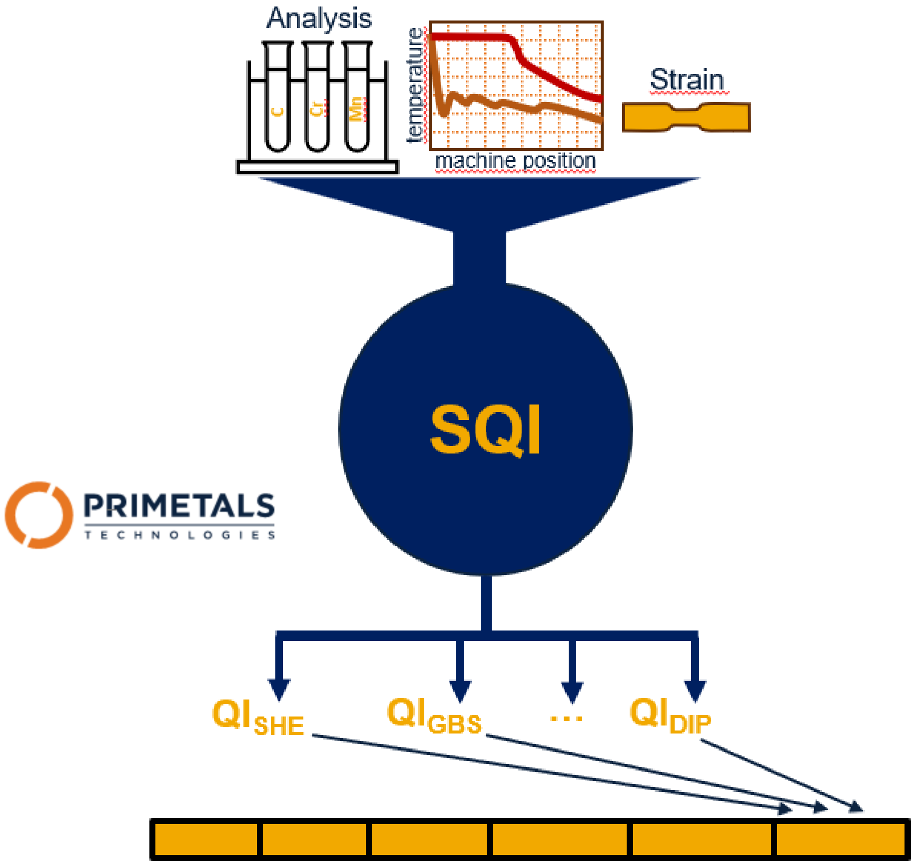


Process & machine

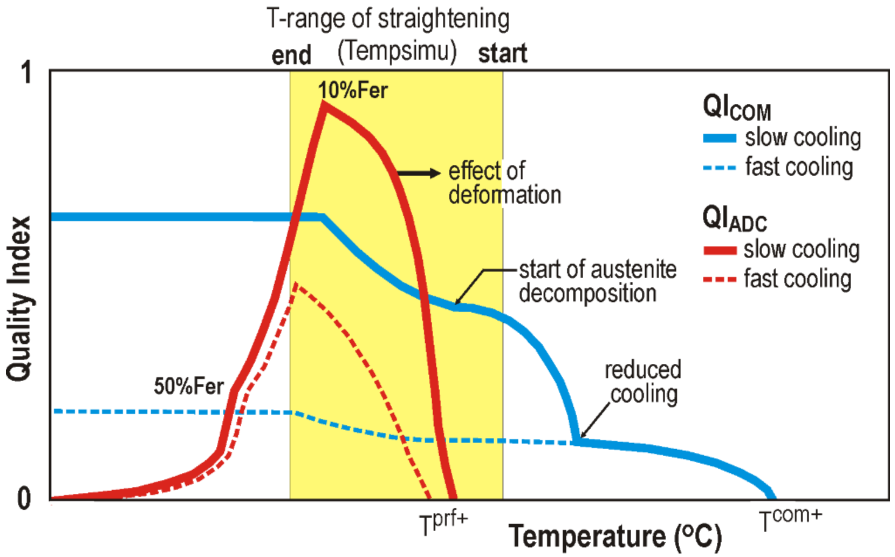
Smart Segment / Pinch Roll

Surface Quality Prediction

- **Online quality prediction: DynaPhase and SQI**

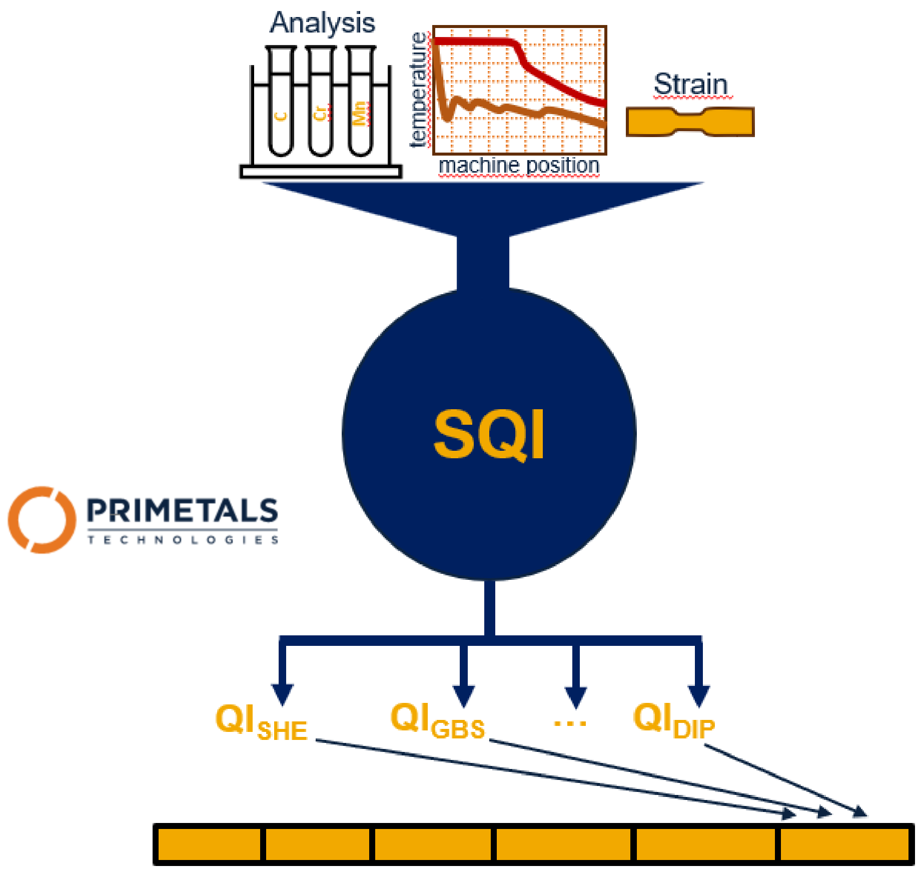


- Calculate QIs for every 1m of strand length
- Feed condensed QIs (not full characteristic) to Quality Expert/TPQC for long-term storage.
- QI_GBS per segment (slightly different process conditions)

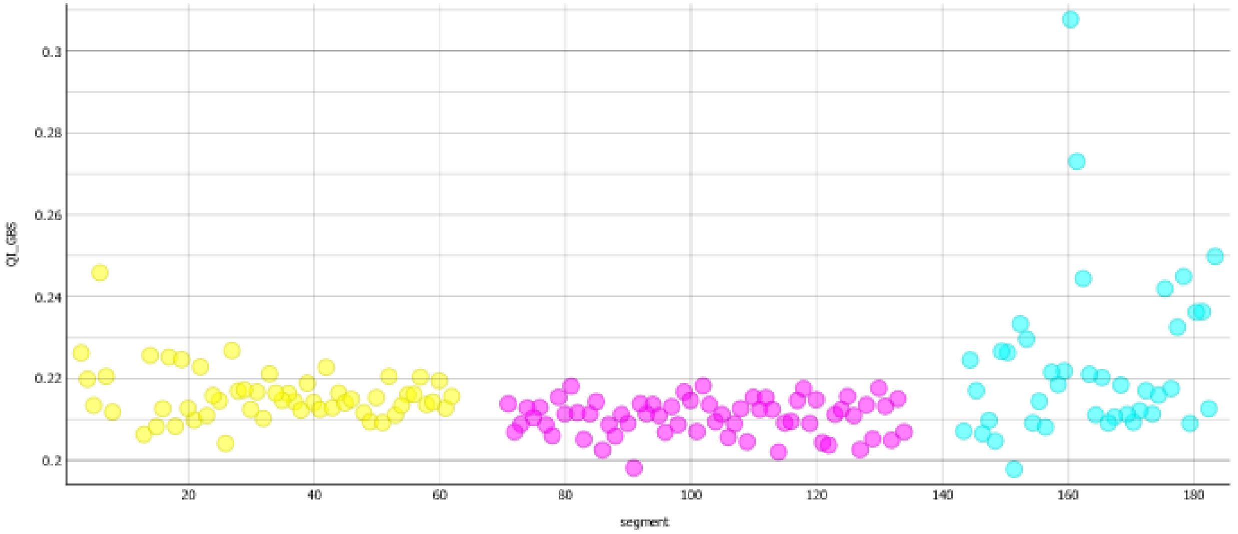


Surface Quality Prediction

◆ Online quality prediction: DynaPhase and SQI



- Calculate QIs for every 1m of strand length
- Feed condensed QIs (not full characteristics) to Quality Expert/TPQC for long-term storage.
- QI_GBS per segment (only slightly different process conditions).

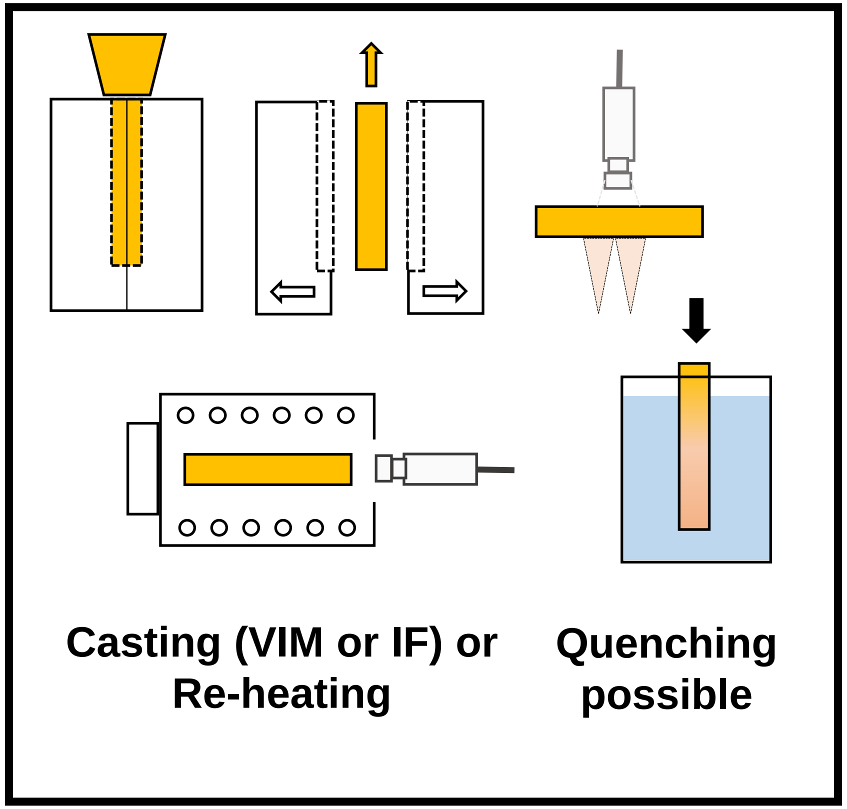


… and what about experiments?

The in-situ bending test (IMC-B)

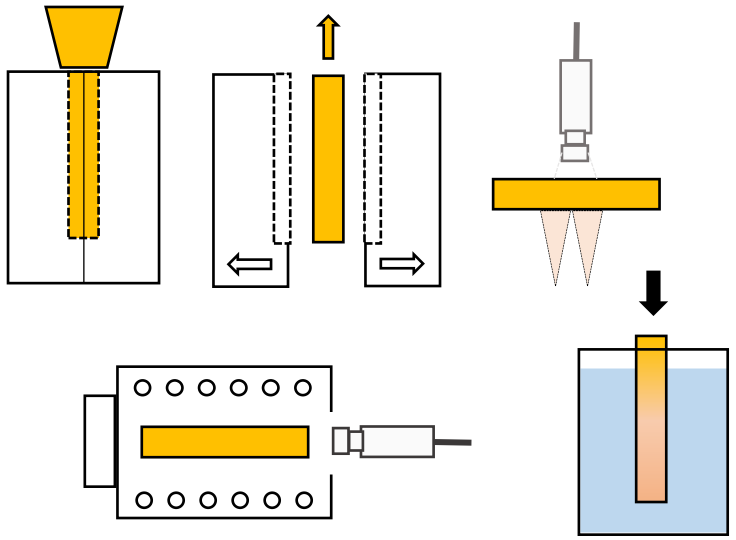
Experiment as training partner: IMC-B-test

- **The IMC-B-test**



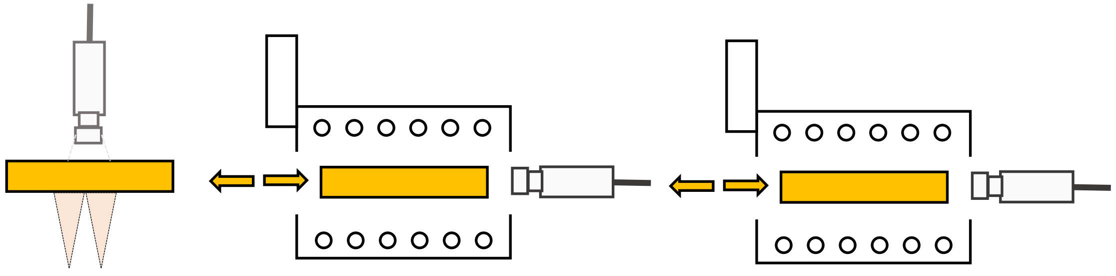
R. Krobath and C. Bernhard, Experimental Quantification of Critical Parameters for Prediction of Surface Crack Formation in Continuous Casting. Steel Research International 76 (2020).

◆ **The IMC-B-test**

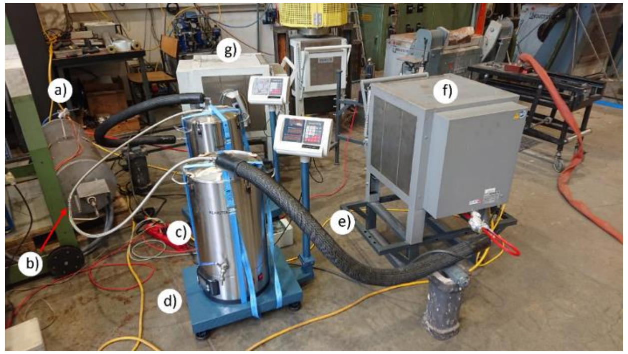


Casting (VIM or IF) or Re-heating

Quenching possible



Controlled cooling (Ar, Air, H_2O)



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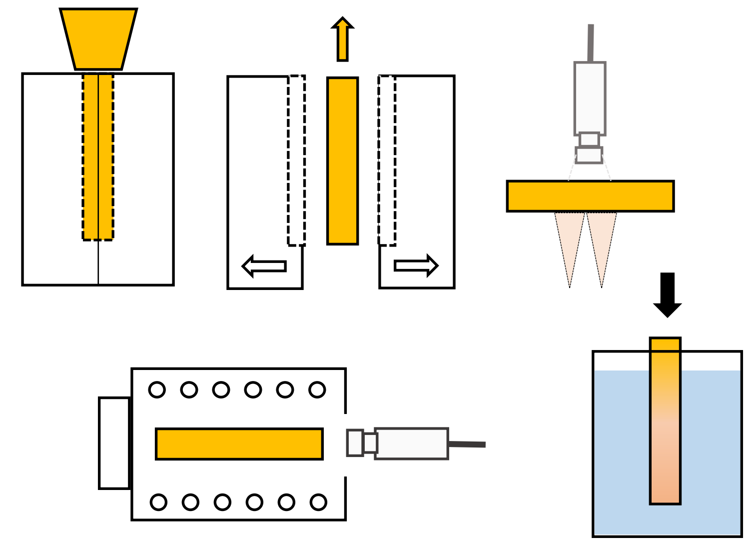
Experiment as training partner: IMC-B-test

PRIMETALS TECHNOLOGIES

◆ The IMC-B-test



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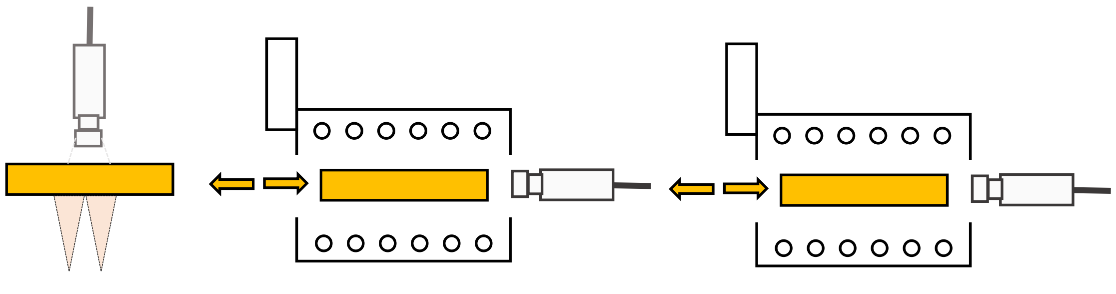

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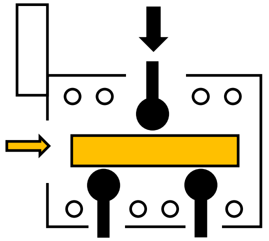
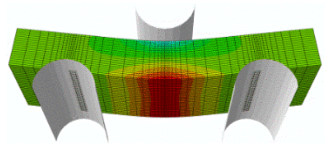
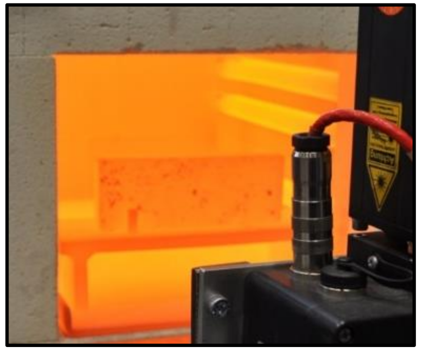
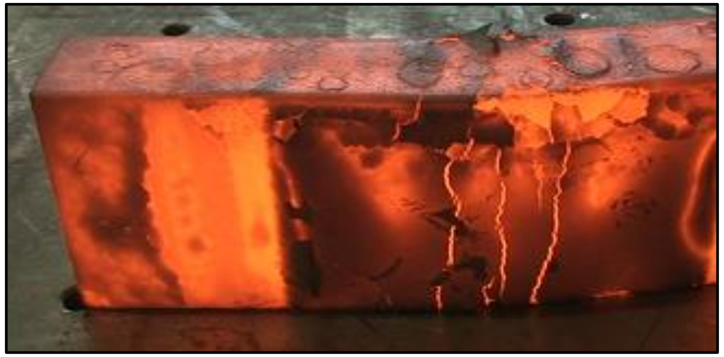


3-Point Bending







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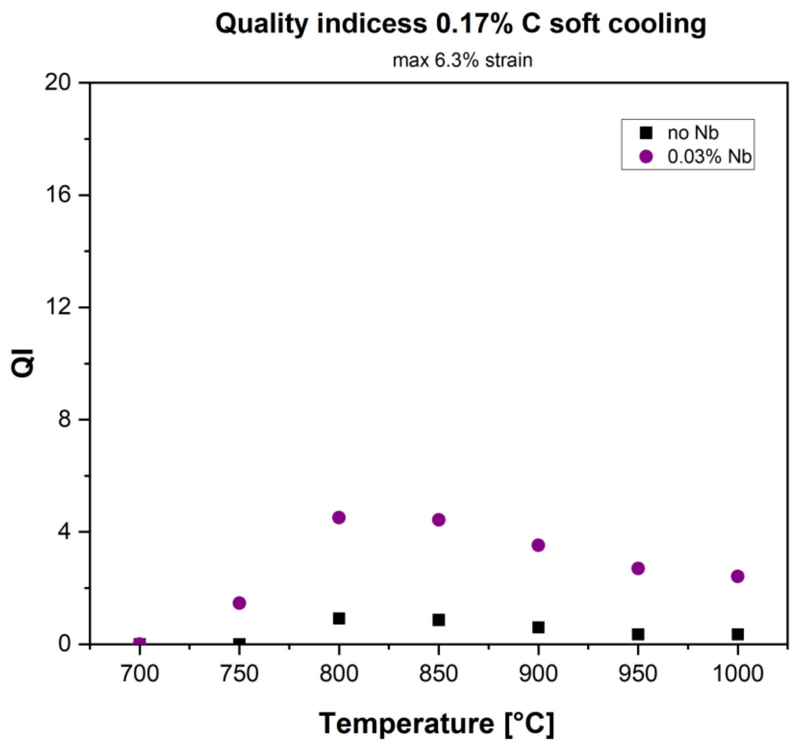
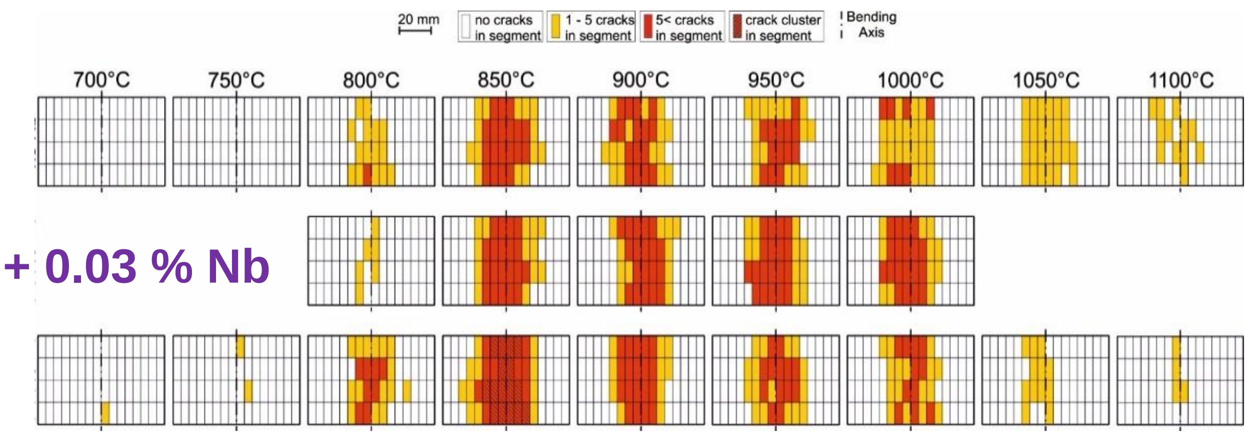
Experiment as training partner: IMC-B-test

- **Influence of Nb(C,N): IMC-B prvides traing data sets for SQI**



C, wt.%	Si, wt%	Mn, wt%	Al, wt.%	N, ppm
0.16-0.18	0.35-0.45	1.40-1.60	0.025-0.045	30-80



S. Hahn, R. Kaltseis, S. Ilie, J. Six, G. Stechauner, P. Presoly, R. Krobath and C. Bernhard, Defect monitoring tool for CC strands. Virtual 9th International Conference on Modeling and Simulation of Metallurgical Processes in Steelmaking (Steelsim), Vienna, Austria (2021).

Experiment as training partner: IMC-B-test

- Medium carbon steel (type Q355)
- Bending temperature 900 °C, bending by 6.2 %.

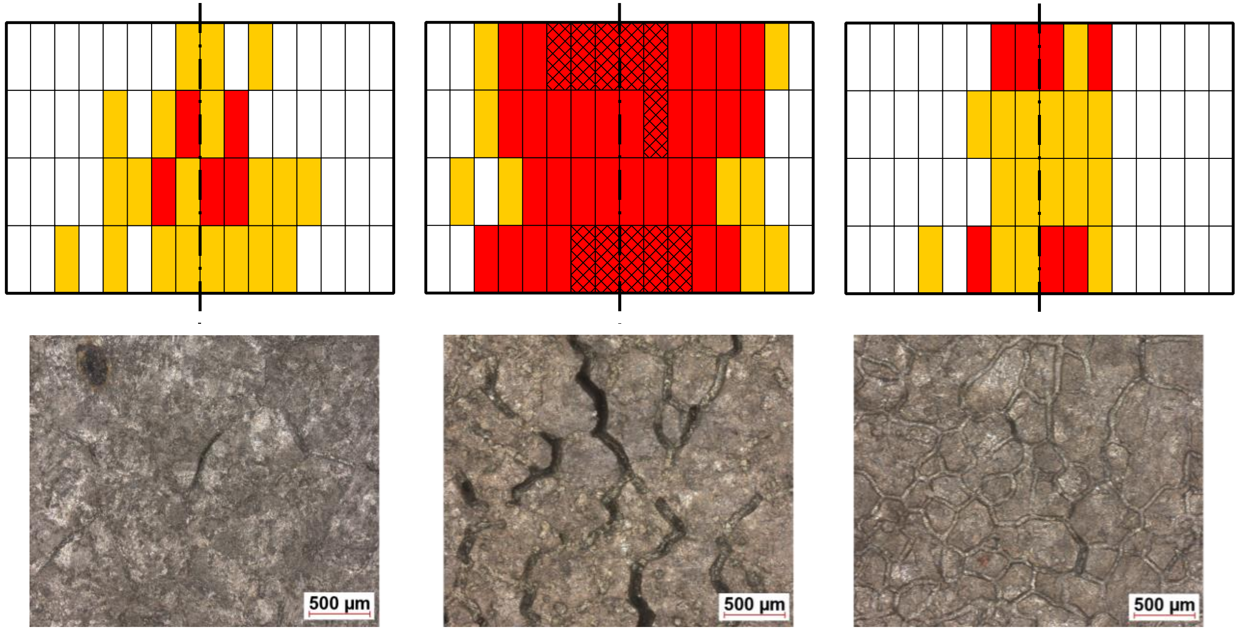
“Reference” Chemical composition [wt.%]				
C	Si	Mn	Al	N
0.17	0.40	1.50	0.030	< 0.008

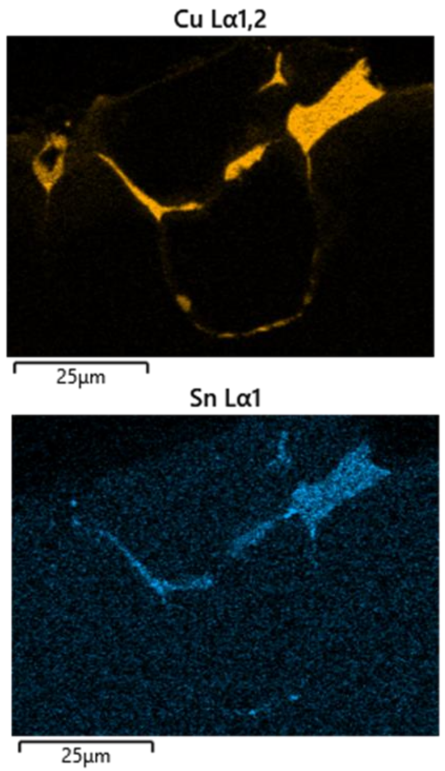
20 mm

no cracks in the segment | 1 to 5 cracks in the segment | 5< cracks in the segment | high number of cracks network cracks / crack cluster

Conventional CC (900 °C)

Medium Carbon | + 0.15 wt.-% Cu + 0.01 wt.-% Sn | + 0.15 wt.-% Cu + 0.01 wt.-% Sn + 0.25 wt.-% Ni





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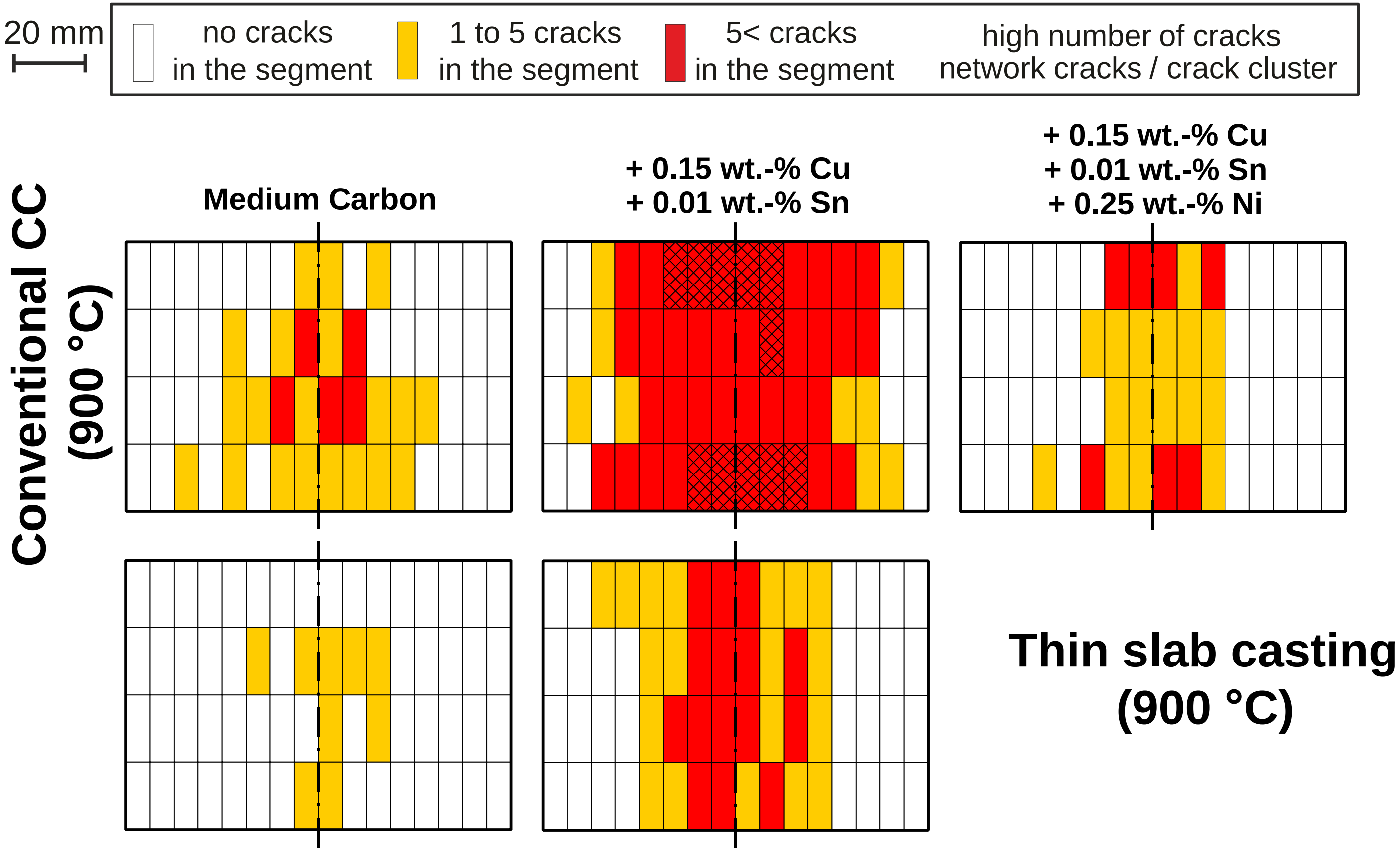

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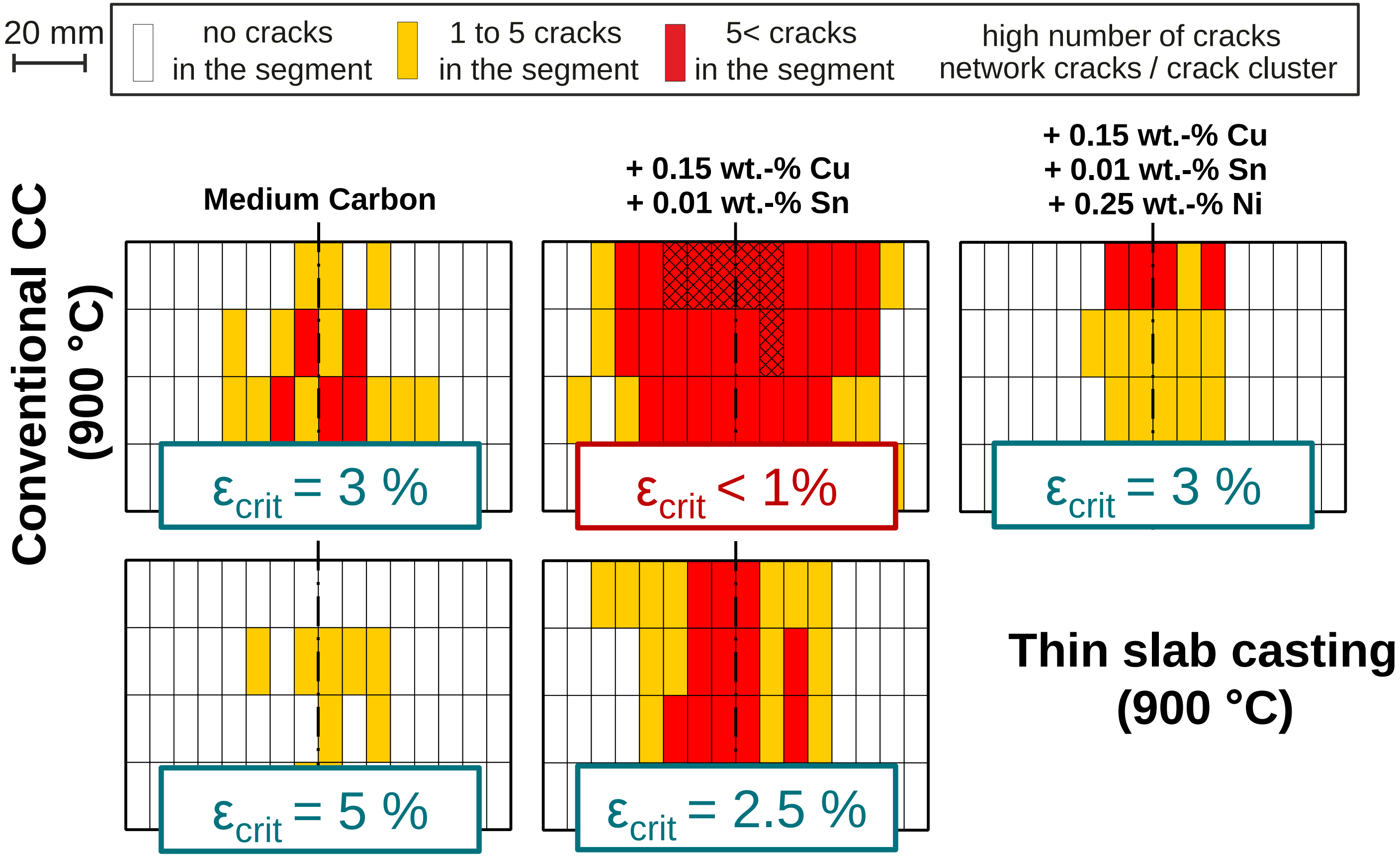
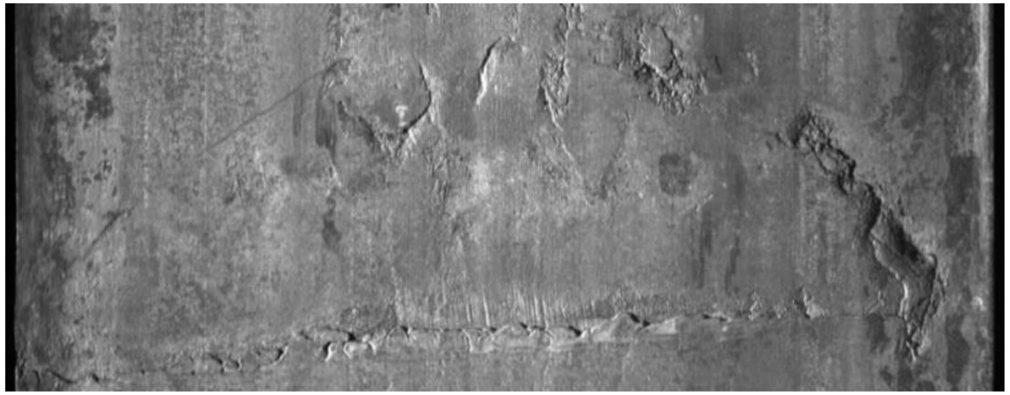


… and new sensors?

Surface Quality Prediction: On-line inspection systems

Main challenges: Temperature, scale, depth of defects, ….

- Electromagnetic systems.
- Optical systems: Example laser (SAPOTECH)
- Ultrasonics.



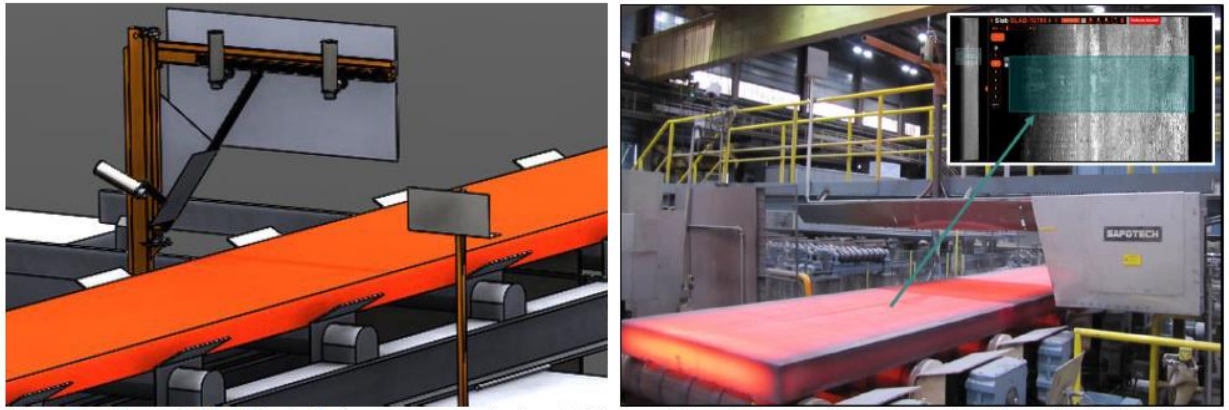
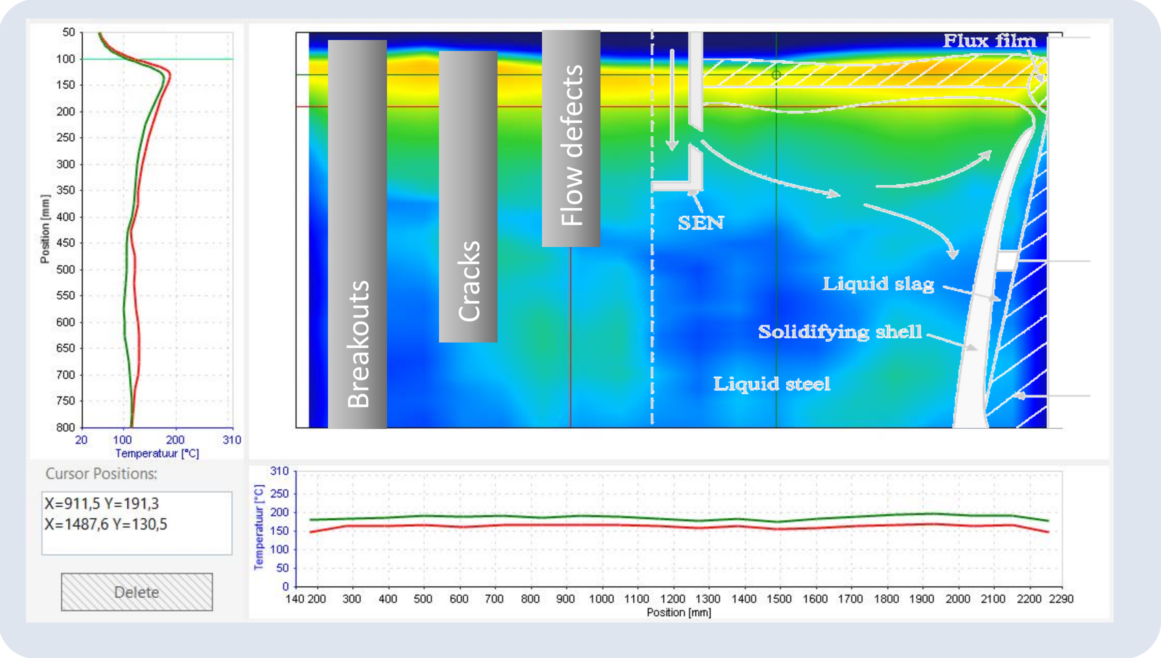


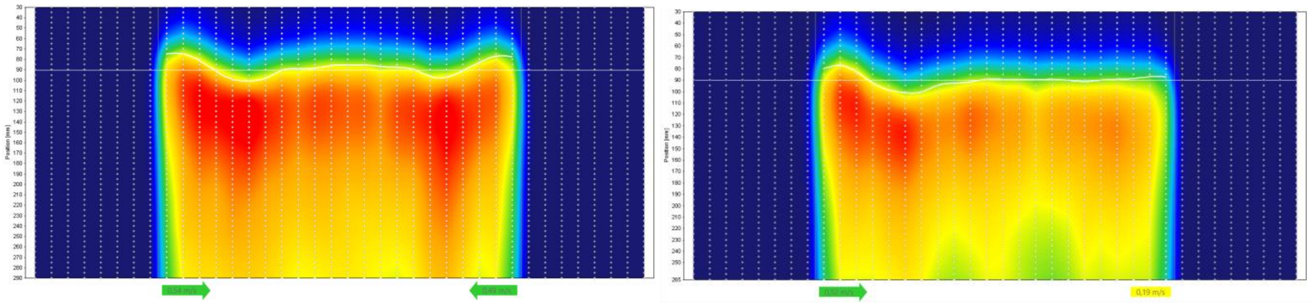
Figure 2: Reveal CAST installed on a turning horizontal beam (a) and on a walkway crossing the roller table (b)

Sapotech. Reveal CAST, available from:
https://www.sapotech.fi/solutions/reveal-cast/

- **Parametrization: Temperature measurement in the cc mold**

- For slabs most common: **Thermocouples.**
- Relatively new: **Fiber optical based mold monitoring.**





Alma Olivos et al., Tata Steel Ijmuiden, IWSQ-2, Bergamo, December 2023

Conclusions

Conclusions

- Numerical simulation will further play a central role in defect prediction.
- For l/s and s predictions, computational thermodynamics (and kinetics) are a central part of defect prediction functions. Microsegregation, microstructure evolution and phase transformation kinetics are essential.
- Phenomenological defect prediction functions are increasingly approaching.
- The potential of a synergy with data-driven approaches should be exploited. New technologies, such as optical temperature measurement, could also provide additional valuable information.
- Limitations due to the lack of divergence of parameters could be solved by experiments as a training partner for defect prediction models.
- New sensors for defect detection will provide more comprehensive data sets.

Technical University Leoben
Ferrous Metallurgy

From phenomenological models to hybrid approaches: quality prediction in continuous casting at a crossroads.

Christian Bernhard, Susanne Hahn and Sergiu Ilie
Michel Bernhard, Peter Presoly, Georg Gaiser, Maximilian Kern, Robert Littringer, Daniel Kavić

6th K1-MET Simulation Conference, Vienna, 2025