CCC Annual Meeting

August 8, 2023

Macro and Micro segregation assessment method for continuous casting wide slabs

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Contents

1. Introduction

1.1 Main Purpose

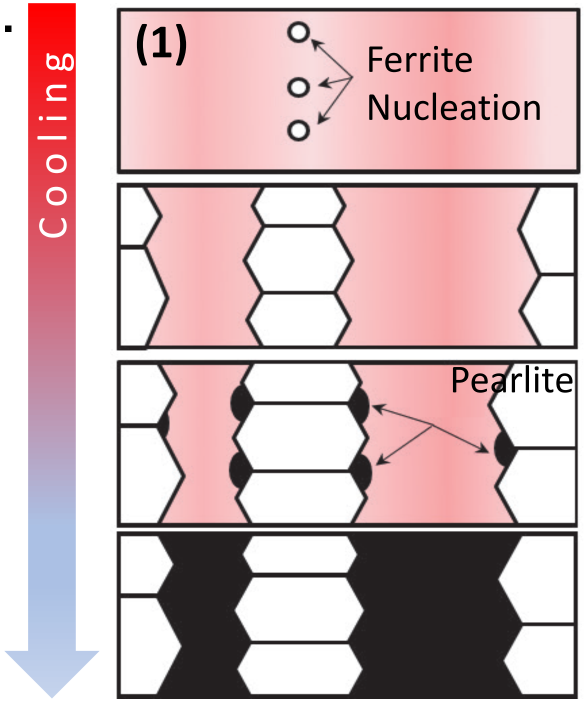
Estimate internal quality of wide slabs performing a comprehensive characterization of their microstructure.

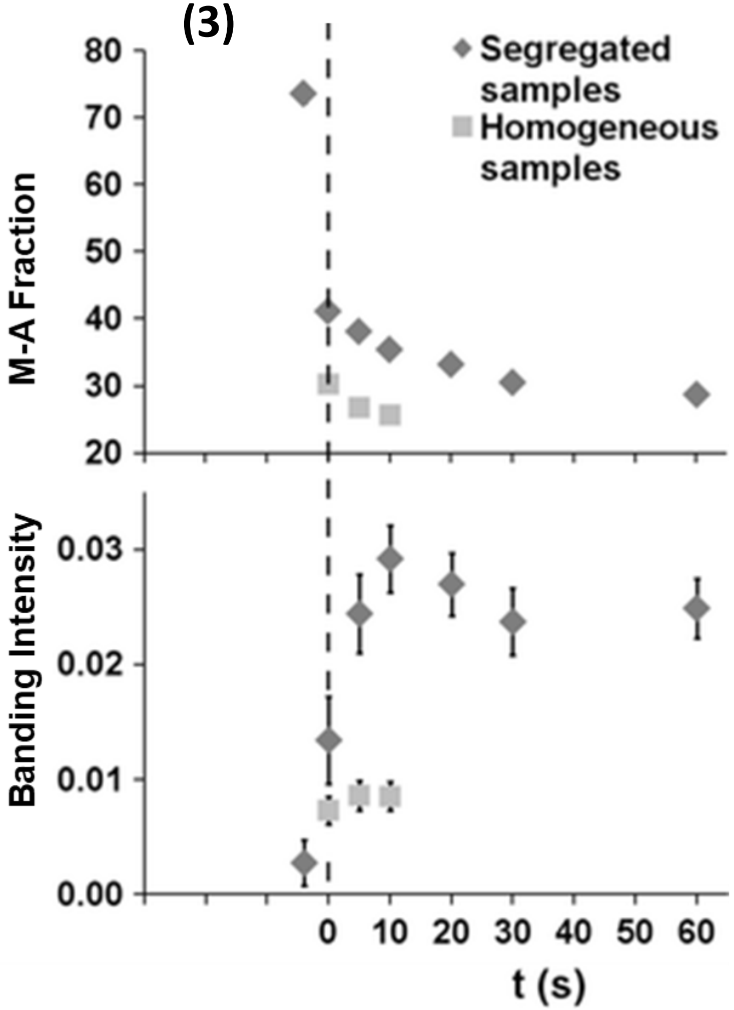
1.2 Technical Relevance

Through an efficient characterization of steel microstructure, alongside processes knowledge, is it possible to have a comprehensive understanding about effects of slab internal quality in rolled products.

1.3 Effects of slab internal quality in rolled products

Micro segregation effect in rolled products microstructure





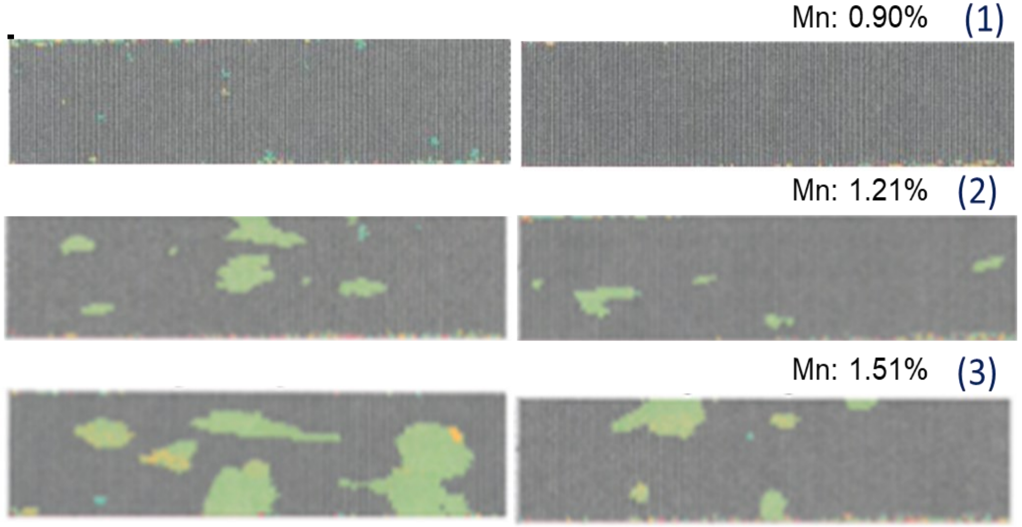
(1) Banding formation
(2) Banded structure: ferrite and pearlite layers
(3) Segregated samples tend to present higher banding levels and brittle constituent M-A (Martensite-Austenite) after accelerated cooling

HUNKEL, M. Seigerungen in Stählen während der Wärmebehandlung - Eine Betrachtung entlang der Prozesskette. Journal of Heat Treatment , v.76, 2021

KREBS, Benoit. et all. Banded structure in Dual Phase steels in relation with the austenite-to-ferrite transformation mechanisms. Journal of Materials Science, v.46, 2011

1.3 Effects of slab internal quality in rolled products

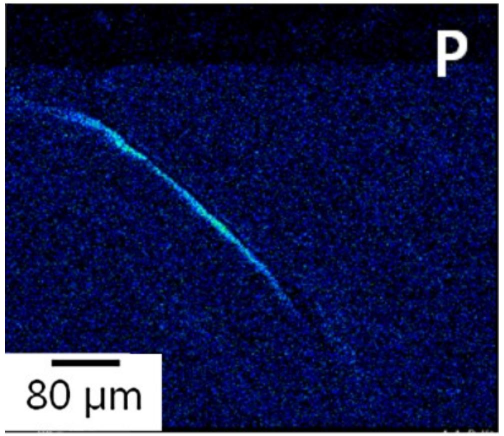
Micro segregation associated to poor performance in service

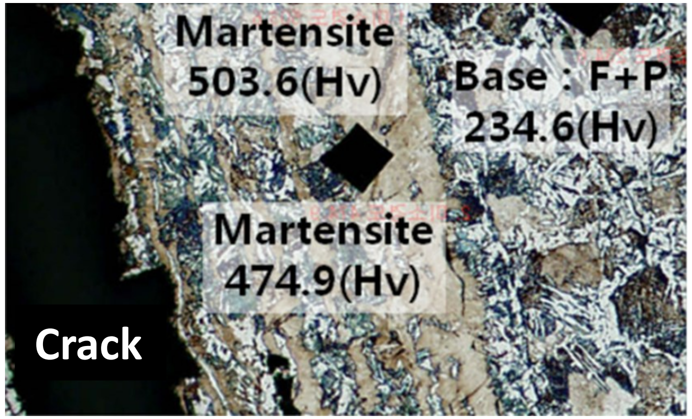


C-scan UT maps after NACE-TM-0284 test: 96h Immersion in A solution (H_2S, NaCl e Acetic Acid). Steels with lower Mn content have better performance.

Steel	Flawless specimens
BMn (1)	100%
MMn (2)	66%
AMN (3)	17%

LOPES, Carlos. Influência dos Teores de Carbono e Manganês no grau de bandeamento microestrutural e na resistência ao HIC de chapas de aço ASTM A516-70 normalizadas, Master Thesis, UFMG, 2011.





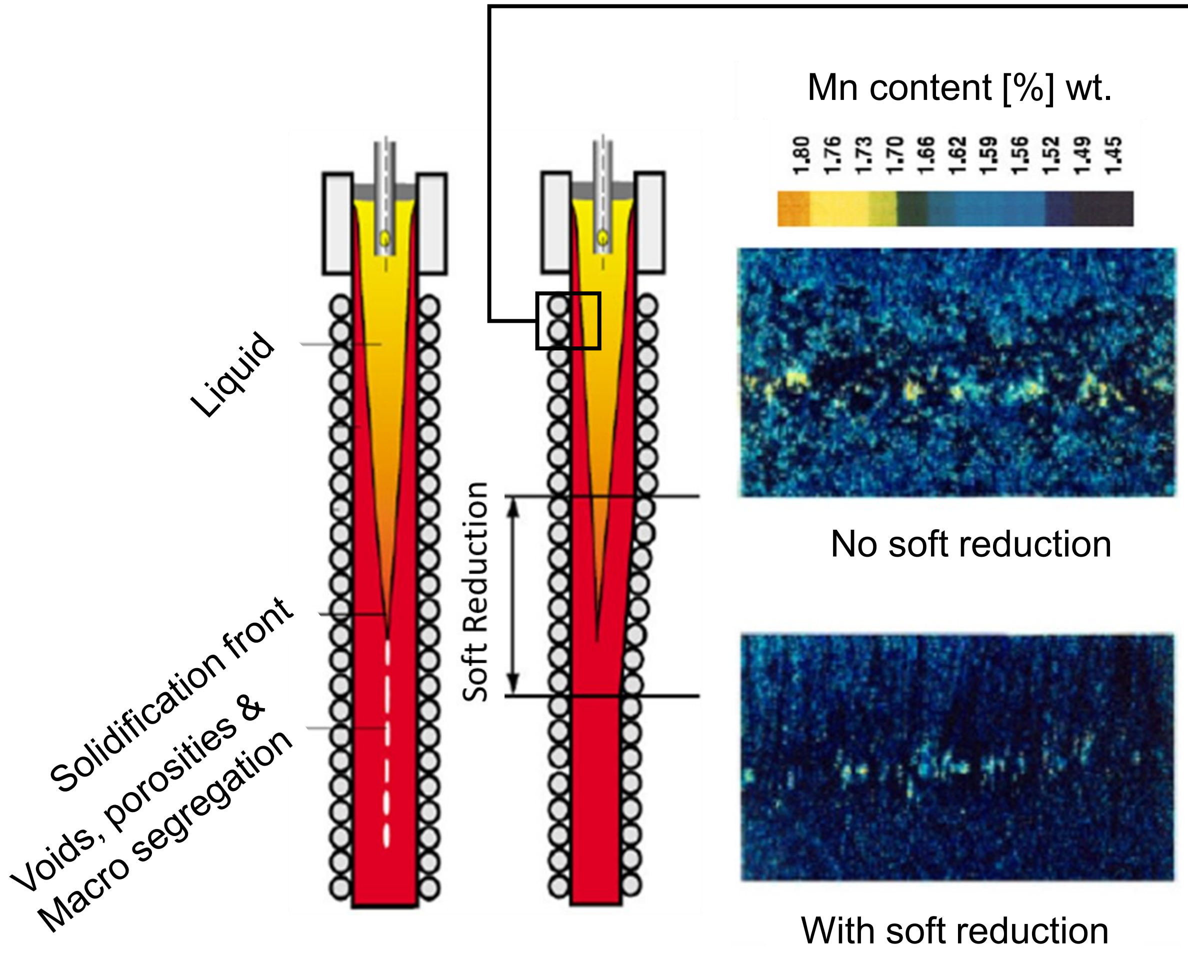
Fragile constituent formation associated Phosphorus micro segregation in a hook crack after ERW welding

MIN, Sung Joo. et all. A Study of Metallurgical Factors for Defect Formation in Electric Resistance Welded API Steel Pipes. Metallurgical and Materials Transactions E, v.2E, 2015

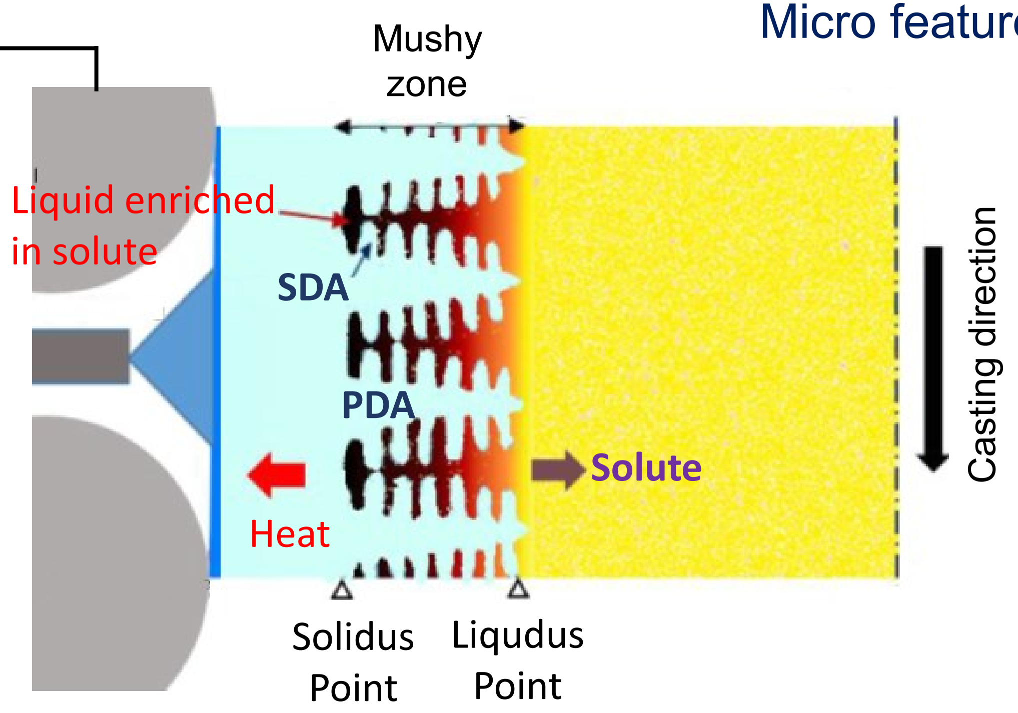
2. Solidification Process in Continuous Casting

Continuous Casting Center

Macro features



Micro features



<u>PDA</u>: <u>P</u>rimary <u>D</u>endrite <u>A</u>rm
<u>SDA</u>: <u>S</u>econdary <u>D</u>endrite <u>A</u>rm

FUJIMURA, Toshio. Solidification and Segregation in Continuously Cast Steel. PhD Thesis, Hokkaido University, 2018.

3. Testing Methods

GERDAU CBMM

3.1 Overview and main features

MICRO APPROACH

CCM
CON1D

CCM
CON1D

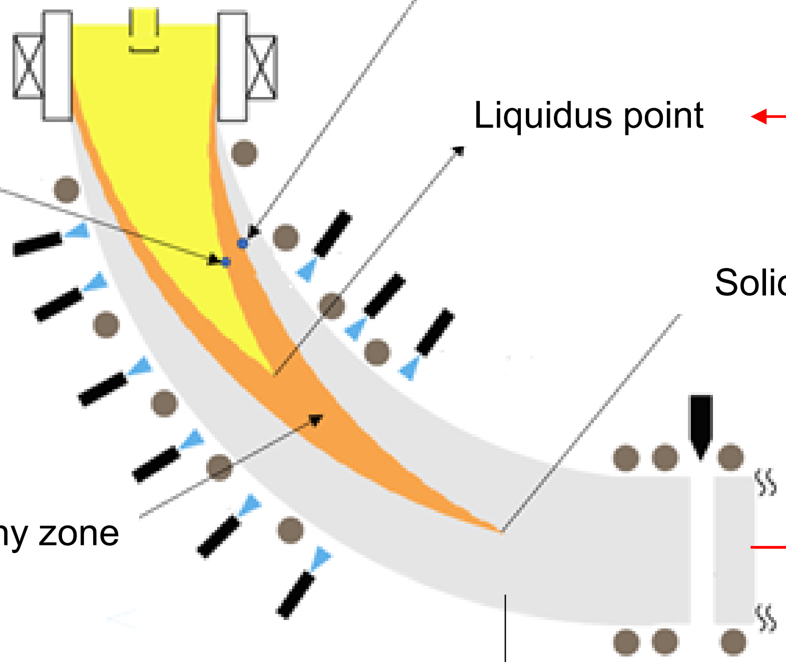
MACRO APPROACH

Solidus point

Liquidus point

Liquidus point

Solidus point

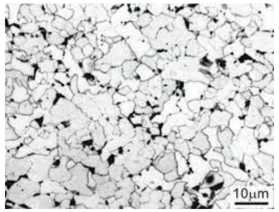


Mushy zone

CCM
CON1D

Chemical composition

Steel matrix microstructure



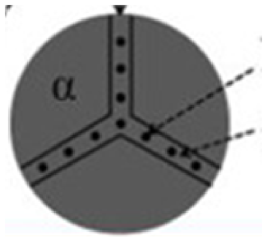
Solidification microstructure

CON1D

SDAS

Precipitates
2nd phase particles

FactSage



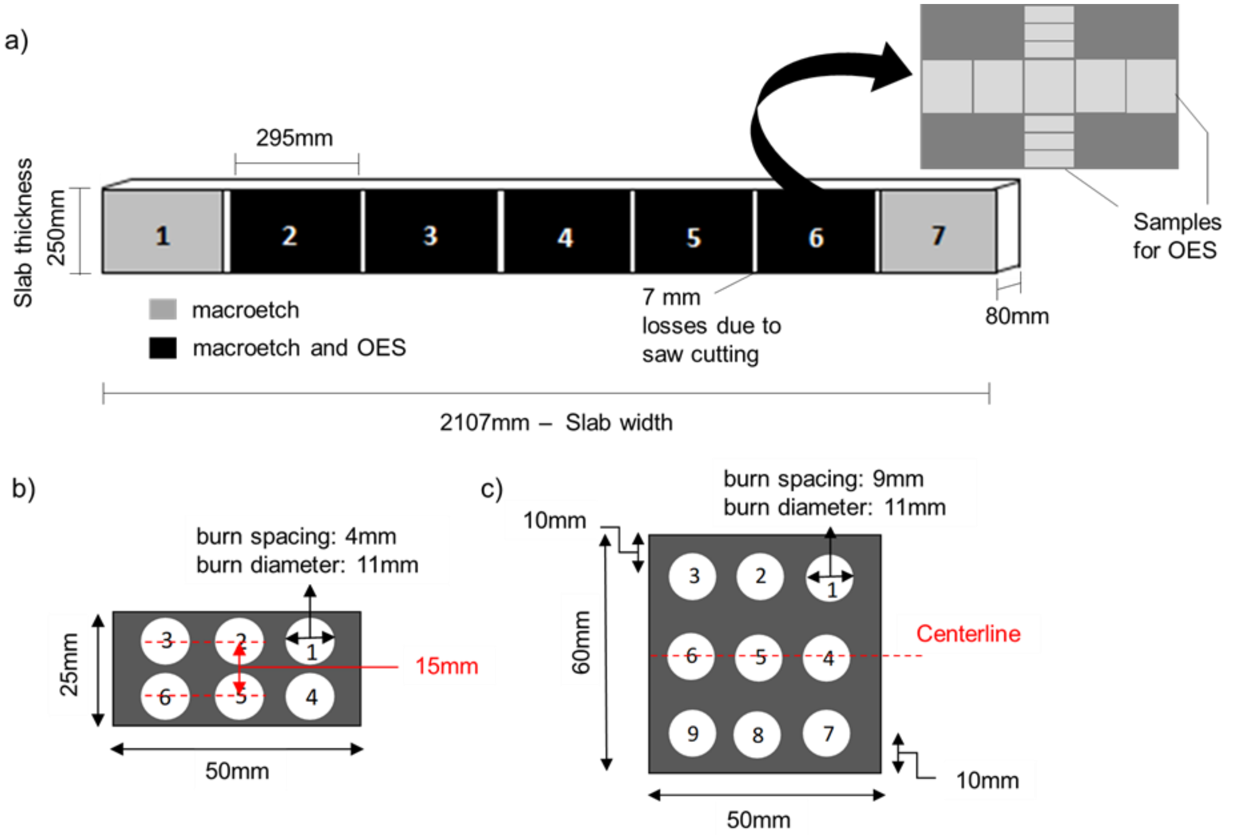
MnS
Nb(C,N)
Ti(C,N)

Keys:
Blue: Calculation tools
Green: Analysis & Measurements

GMS Melo et al.

3. Testing Methods

3.2 Macro approach



(a) Samples for macro-etch taken from slab width, detailing smaller samples for OES. (b) Thickness-wide sample for OES. (c) Width-wide sample for OES. Numbers 1 to 6 in (b) and (c) means individual OES burns.

Base chemistry of test heat – mass content in %wt

C	Mn	Nb	Ti	P	S
0.15	1.35	0.026	0.015	0.021	0.005

➔ **Steel grade**: regular 50ksi HSLA grade;

➔ **Chemical element selection premise**:
- **Mn**: major alloy element – relevant sulfide formation: MnS;
- **All other elements**: high partition & diffusion coefficients in delta ferrite and austenite – prone to segregate even with one/two magnitude order lower (% wt.) when compared to Mn

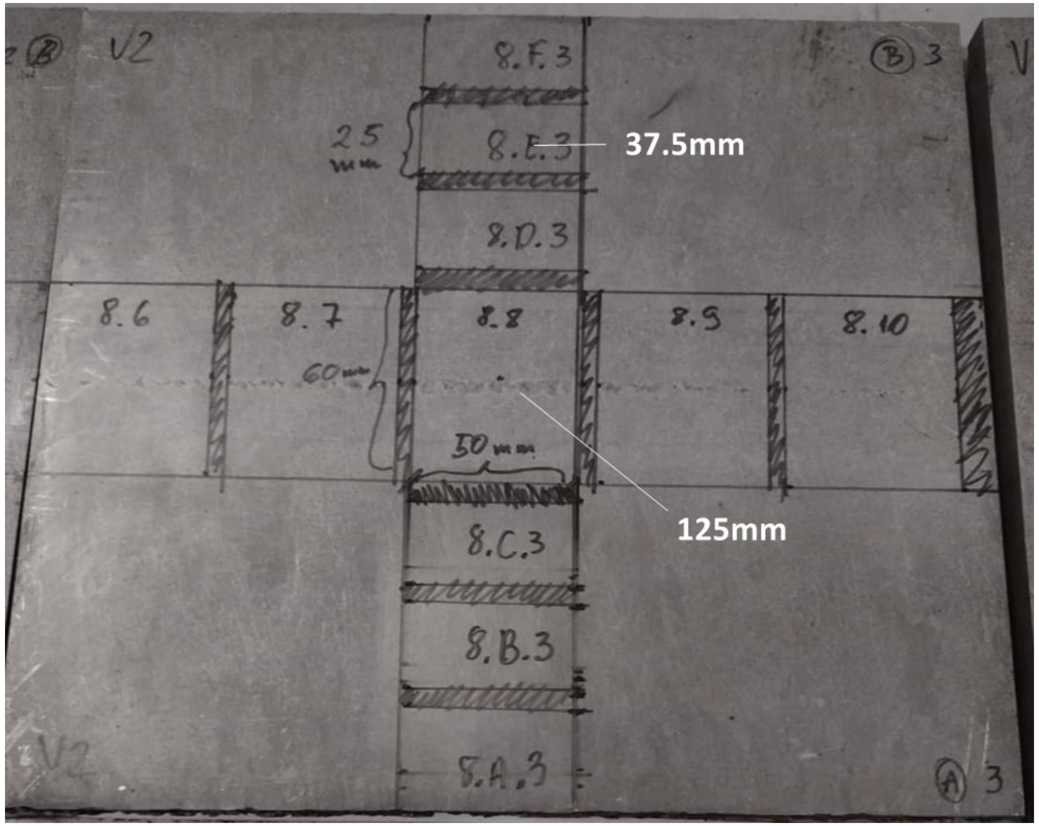
3. Testing Methods

3.3 Micro approach

After identifying the fields of higher concentration that define centerline segregation, among the samples 2 – 6 (figure 1a), it was selected two samples: one that has fields with higher concentration and another one without pronounced segregation

- **Steel matrix and solidification microstructure**: 37.5mm below slab top surface (inner radius) and centerline to compare the differences between last portion to solidify (centerline: 125mm) and an intermediate point;

- **Second phase particles in centerline**: SEM-EDS;



An example of macro etch sample took from the slab and measurements positions from the surface;

4. Calculation Methods

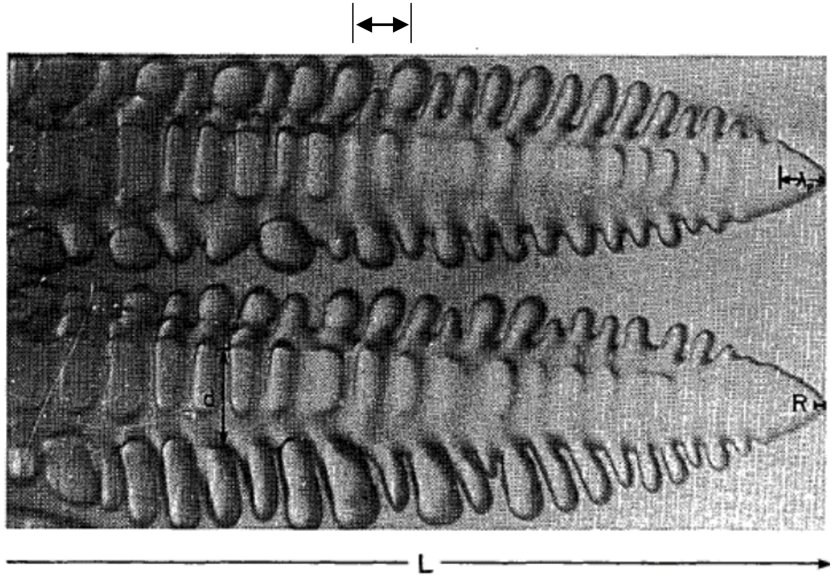
➔ **Liquidus Temperature:**
- CCM: data from L2 caster supplier
- CON1D: based on pseudo-binary Fe-C (variable), Mn, Si, P, S, Nb, Ti, V, Cr, Cu, Ni, Mo, N (defined)
  $T_{liq} = 1536 - \Sigma (m_e * p_e)$

➔ **Solidus Temperature:**
- CCM: data from L2 caster supplier
- CON1D: $T_{sol}(i) = 1536 - \Sigma m_i * cl_i$
  where $cl(i) = p_e * ((1+fs(i)) * \beta_e * (k_{e_f} - 1))^{((1-k_{e_f})/(\beta_e * (k_{e_f} - 1))}$

➔ **Liquidus & solidus positions:** iterative calculation depending on chemistry, casting speed, simulated length, cooling recipes…etc;

➔ **Precipitation and 2nd phase particles:** FactSage 8.2 Equilibrium cooling with back-diffusion – Equilib module

SDAS: Secondary **D**endrite **A**rm **S**pacing



PDAS: Primary **D**endrite **A**rm **S**pacing

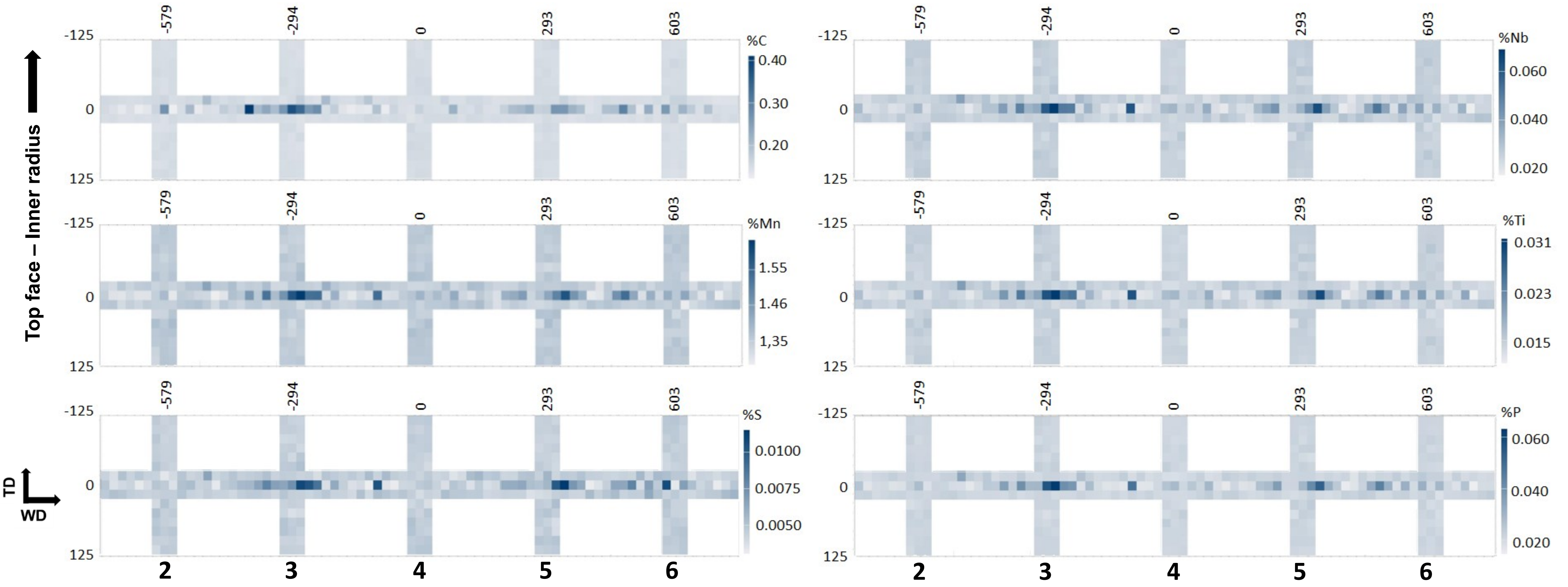
➔ **Measurements:** Optical microscope – linear intercept
SDAS = L/(N – 1)

➔ **CON1D calculation:** WON e THOMAS, 2001:
$C \leq 0.15\%$: $SDAS = (169.1 - 720.9 * p_c) * CR^{-0.4935}$
$C > 0.15\%$: $SDAS = 143.9 * CR^{-0.3616} * p_c^{(0.5501 - 1.996 p_c)}$

5. Results and discussions

5.1 Macro analysis

Concentration map for C, Mn, Nb, Ti, S and P, considering slab thickness-wise and width-wise directions.

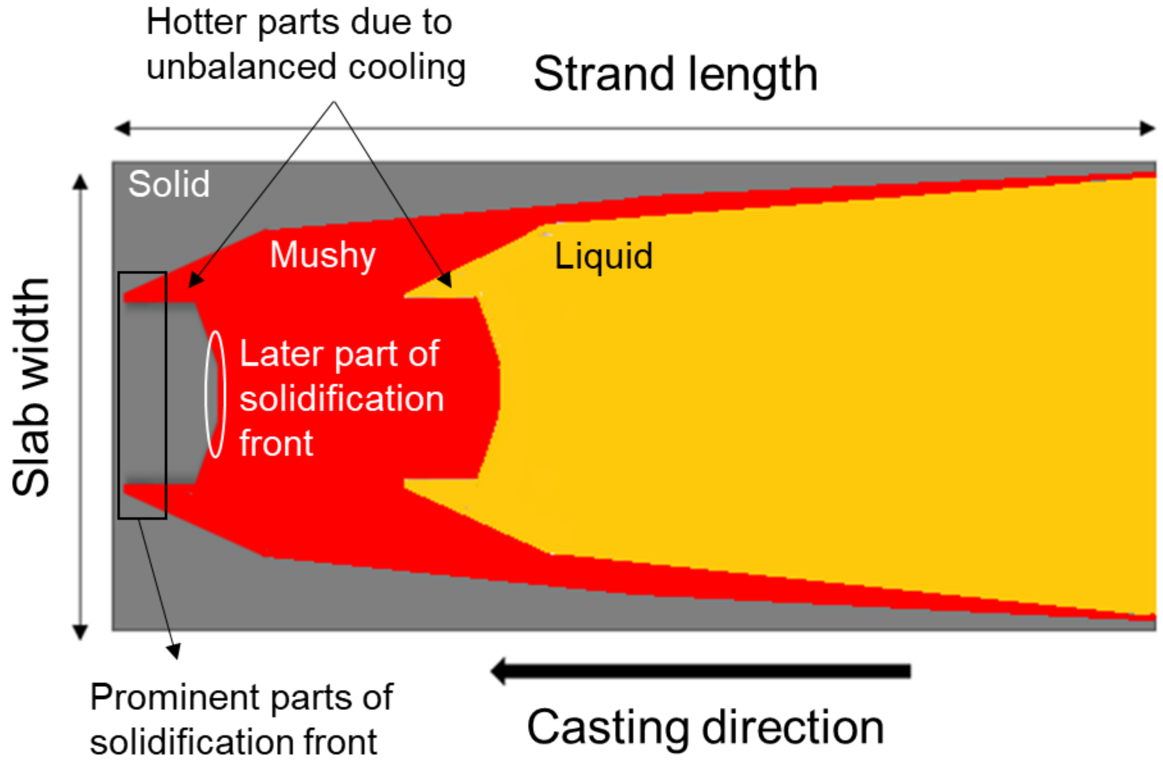


TD: Thickness Direction.
WD: Width Direction.

Samples 2 to 6.
Thickness and width are given in millimeters.

5. Results and discussions

5.1 Macro analysis



Probable solidification front pattern due to unbalanced cooling across slab width.

➔ **Element mass content in segregated regions:** Wang et al. reported that an increase of 3.3 times in C concentration was found for wide and heavy peritectic slabs with 0.13% wt. as base concentration

➔ **PROBABLE CAUSES:**

- **U pattern solidification front**: unbalanced cooling across slab width;
- **Possible trapping** of enriched final liquid (prominent parts) after soft reduction;

Both reported as root cause by Li et al. and Long & Chen

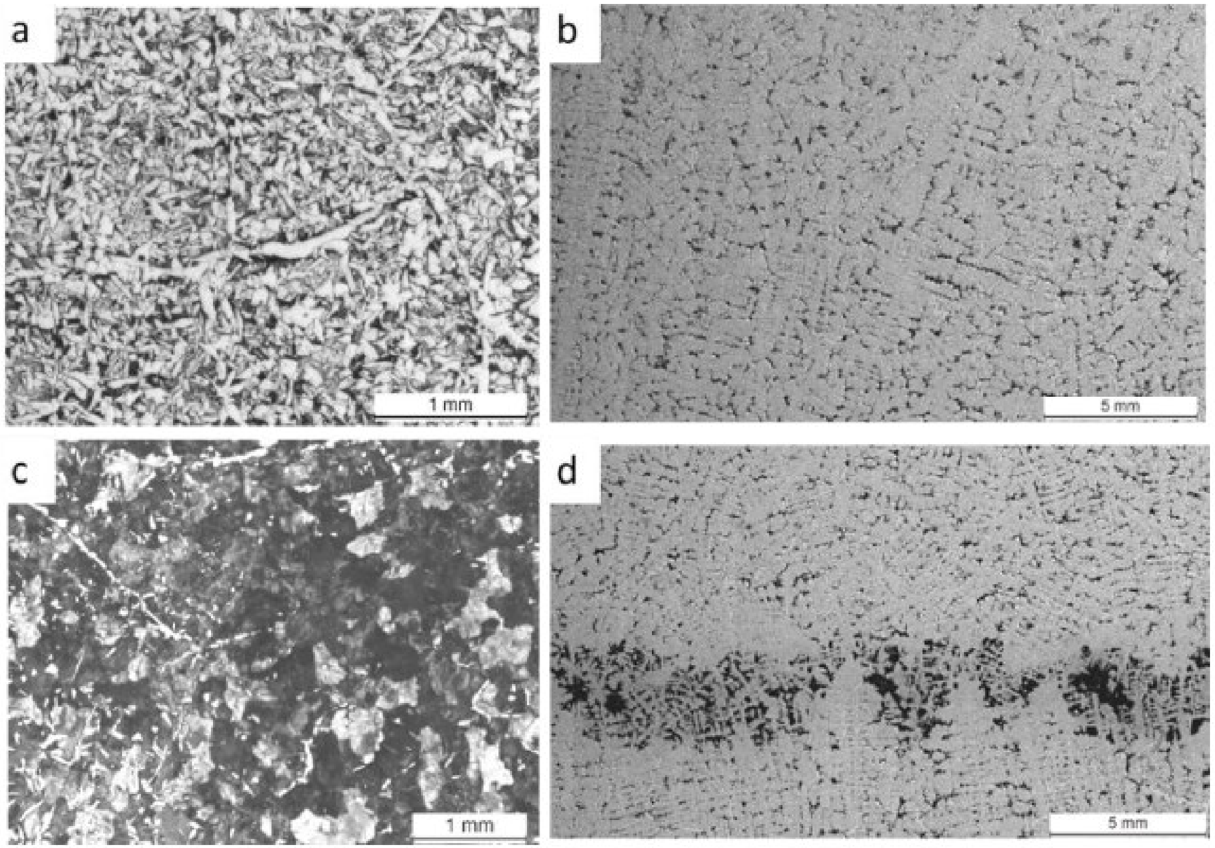
WANG W., ZHU M., CAI Z., LUO S., JI C. Micro-Segregation Behavior of Solute Elements in the Mushy Zone of Continuous Casting Wide-Thick Slab. Steel Res. Int. 2012;83:1152-62

LI J., SUN Y-H., AN H-H., NI P-Y. Shape of slab solidification end under non-uniform cooling and its influence on central segregation with mechanical soft reduction. Int. J. Miner. 2021;28(11):1788-98.

LONG M., CHEN D., Study on Mitigating Center Macro-Segregation During Steel Continuous Casting Process. Steel Res. Int. 2011;82:847-56.

5. Results and discussions

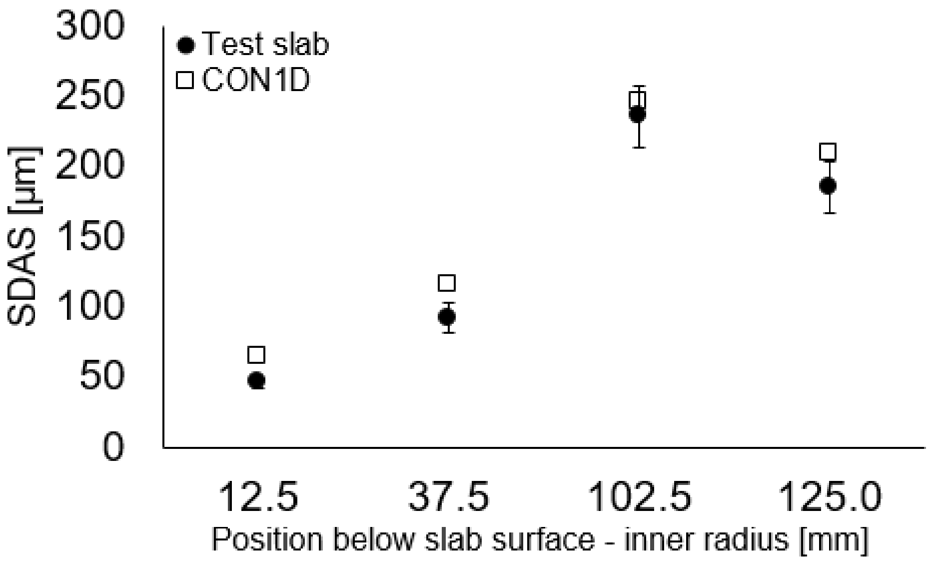
5.2 Micro analysis – Sample 3 (worst macro sample)



37.5mm under slab top surface

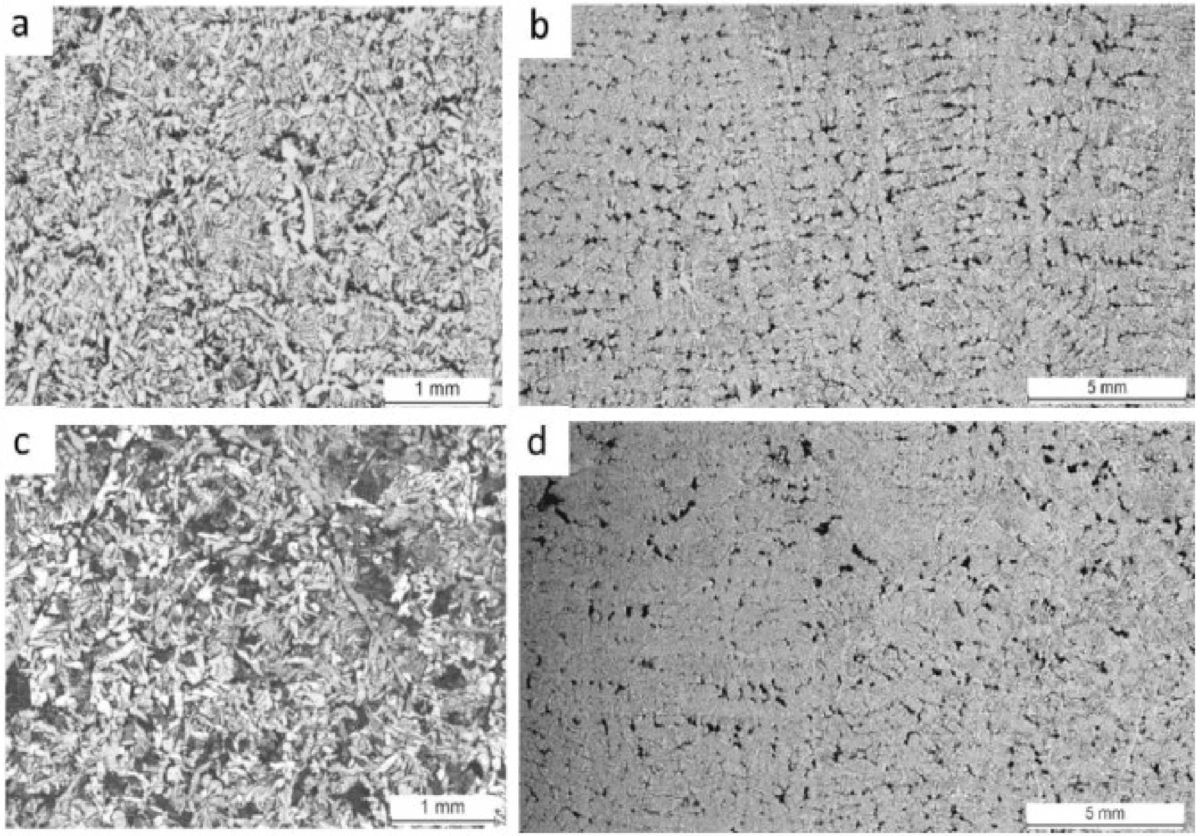
125mm under slab top surface (slab centerline)

Microstructure of sample 3. (a) and (b) show microstructure observed at 37.5mm below top surface – inner radius. (c) and (d) microstructure observed in centerline segregation



SDAS comparisons between Test slab and CON1D. Upper and lower bars mean one standard deviation of measurements (N) in test slab for each position.

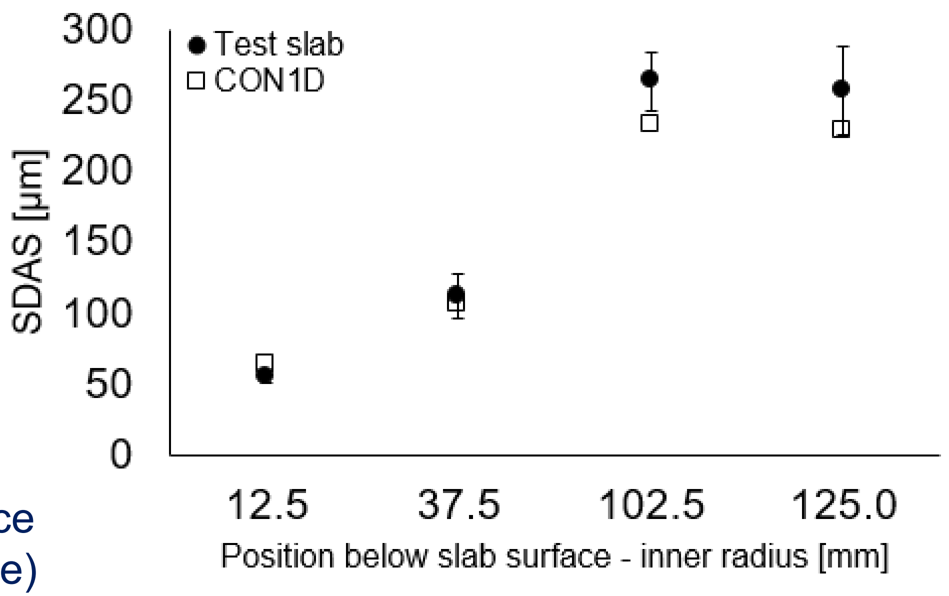
5.2 Micro analysis – Sample 4 (best macro sample)



37.5mm under slab top surface

125mm under slab top surface (slab centerline)

Microstructure of sample 3. (a) and (b) show microstructure observed at 37.5mm below top surface – inner radius. (c) and (d) microstructure observed in centerline segregation

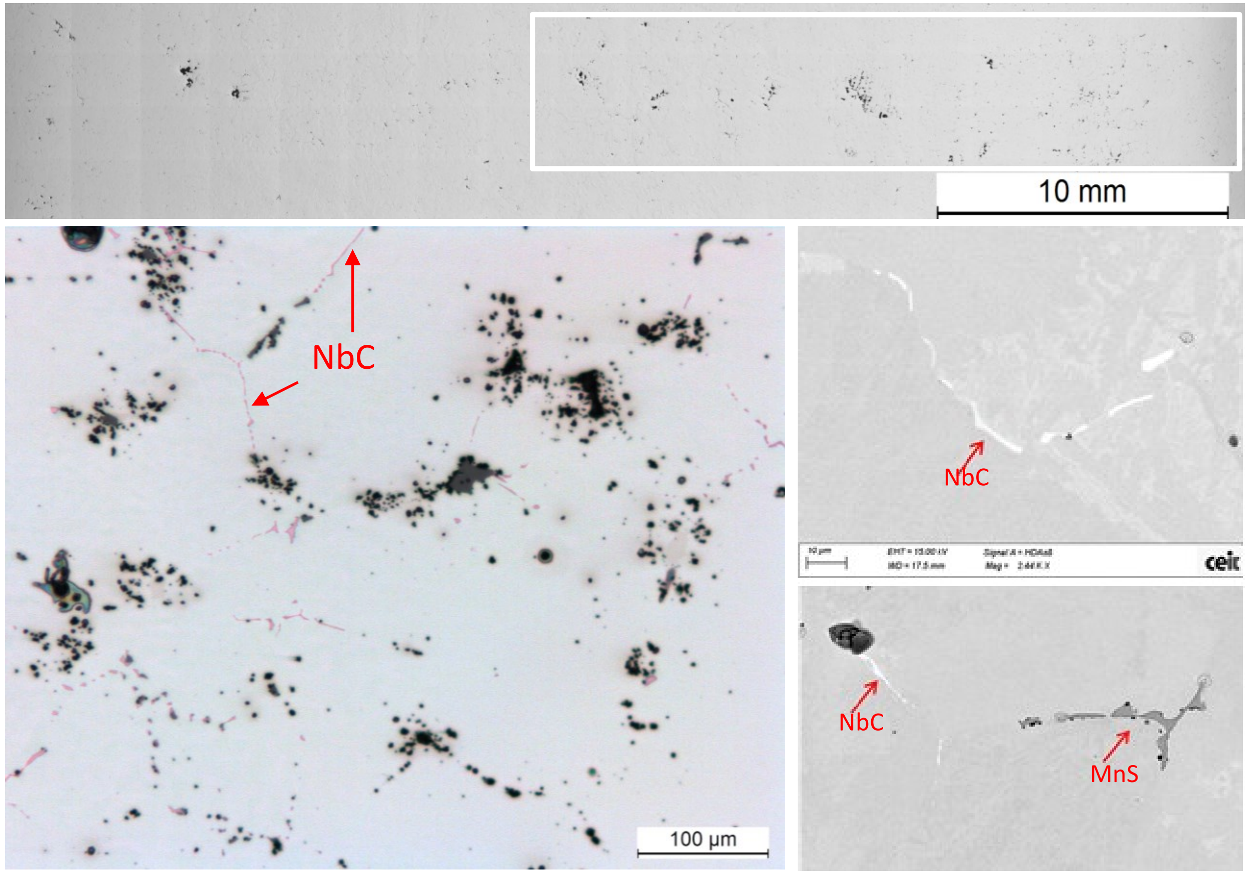


SDAS comparisons between Test slab and CON1D. Upper and lower bars mean one standard deviation of measurements (N) in test slab for each position.

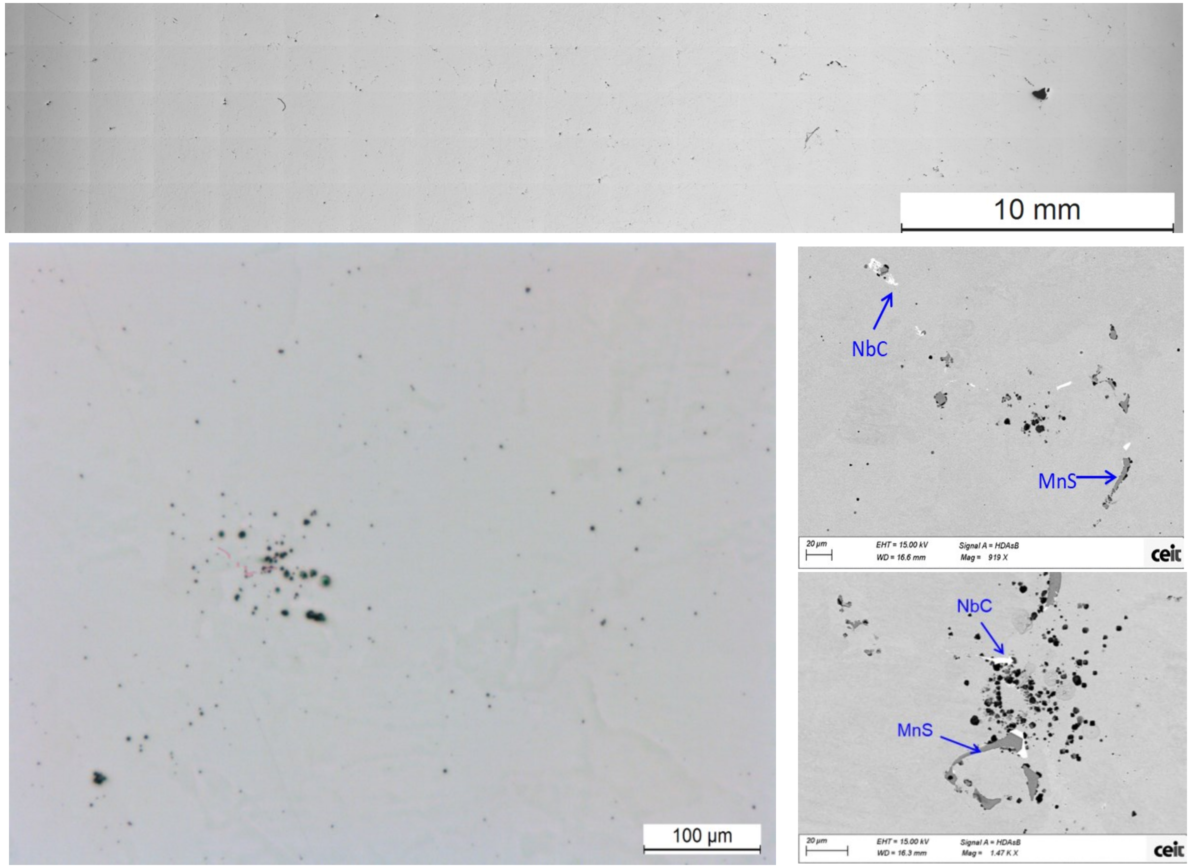
5. Results and discussions

5.2 Micro analysis – Second phase particles in centerline

Sample 3

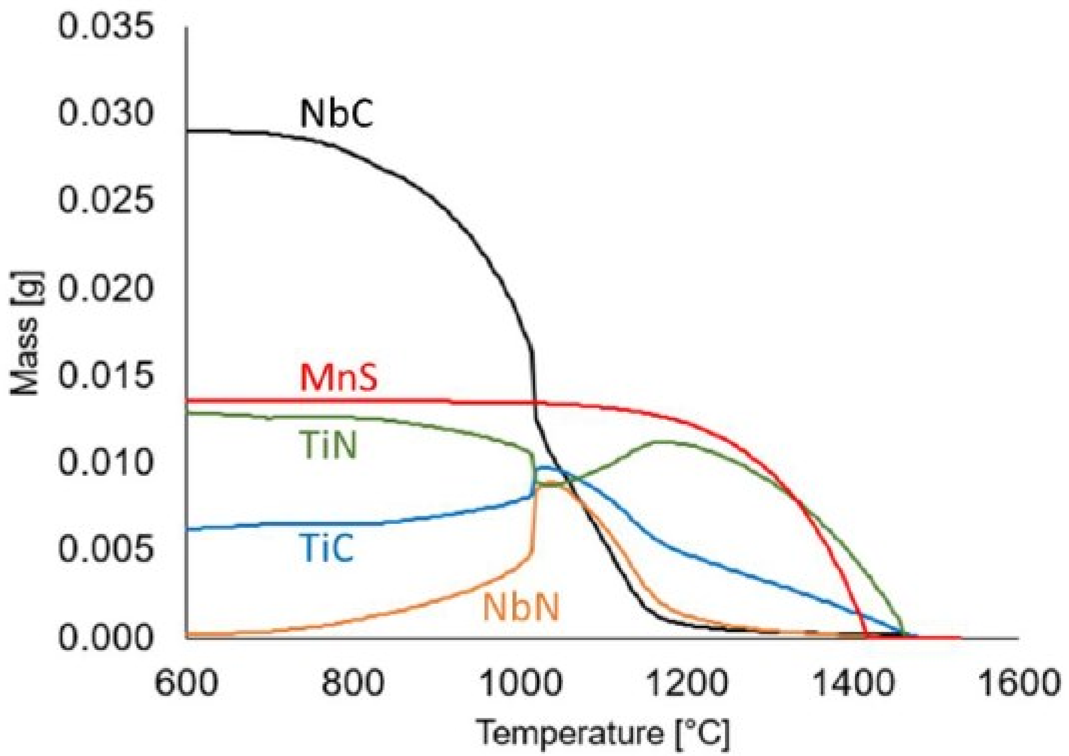


Sample 4



5. Results and discussions

5.3 Calculations



Second phase mass contents using equilibrium cooling with back diffusion in Equilb module of FactSage 8.2.

➔ **Prediction presented good agreement with SEM analysis**

➔ **NbC and MnS:** both most relevant 2nd phase particles;

➔ **TiN could not be seen** probably due to microscopes resolutions (Optical and SEM) used in this present work: particles <2μm cannot be identified accurately

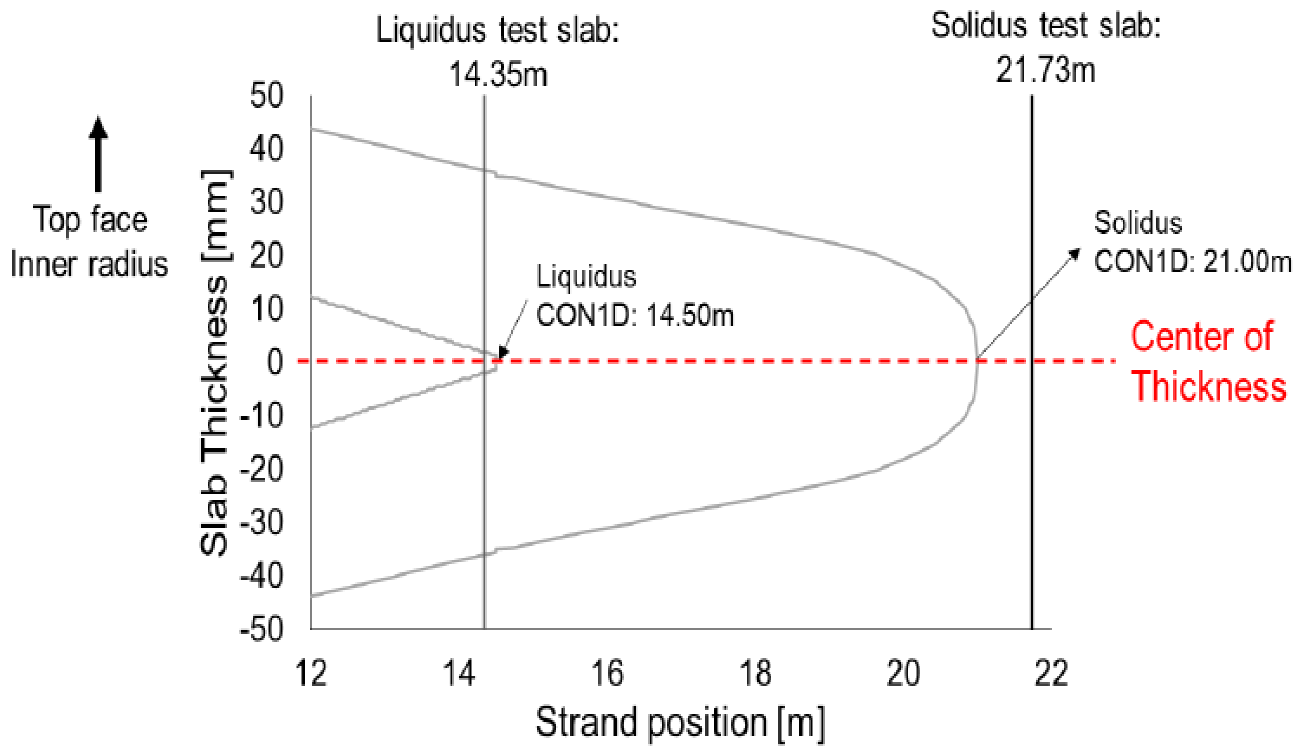
Stock reported **that less than 10% of TiN precipitates of HSLA Nb-Ti grade cooled under a typical slab center cooling rate** (0.1 °C/s - for instance, CON1D predicted for this present work 0.13 °C/s) **are larger than 1μm**. According to Stock and Muller, another equipment, like TEM or STEM should be used.

STOCK J. NbC and TiN Precipitation in Continuously Cast Micro Alloyed Steels [thesis]. Golden: Colorado School of Mines; 2014.

MULLER C-E. Precipitation during continuous casting [dissertation]. Berlin: Technischen Universität Berlin; 2015.

5. Results and discussions

5.3 Calculations



Representation of a longitudinal view of strand mushy zone, with liquidus and solidus point comparisons between caster data and CON1D estimations

Temperature calculation comparison

Temperature	CCM	CON1D	FACTSAGE
Liquidus	1514°C	1514°C	1513°C
Solidus	1453°C	1460°C	1455°C

➔ **Predictions have good agreement with CCM data**

➔ **Liquidus point**: difference of 150mm is small when compared to roll diameter (230mm) and segments (1920mm). It suggests that difference between CON1D and caster data is lower than a roll.

➔ **Solidus point** was estimated by CON1D as 730mm earlier than caster data. At 21m inside the caster (roll dia. 300mm) the difference between CON1D and CCM data are almost 2.5 rolls.

6. Conclusions

➔ **Segregation pattern probably comes from an unbalanced cooling across the slab width,** which leads to an irregular ("U-shape") solidification front.

➔ **Higher solute concentration is linked to presence/quantity of second particle phases.** In other words, it means that macro segregation is not only about simply a solute concentration matter, but also about second particles phases.

➔ **CON1D present itself as a good and reliable tool for simulation,** once its estimations for SDAS, mushy zone length, liquidus and solidus positions presented good agreement with measured values (SDAS) and caster industrial data