Internal segregation cracks: Ghost lines

INFLUENCE OF COMPOSITION AND CASTING PARAMETERS ON THE CRACKING OF CONTINUOUSLY CAST BILLETS

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Process Department

Sidenor I+D

European Commission

Research Fund for Coal & Steel

Internal segregation cracks: Ghost lines

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1. Introduction

Internal and surface defects

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8. Powder entrapment

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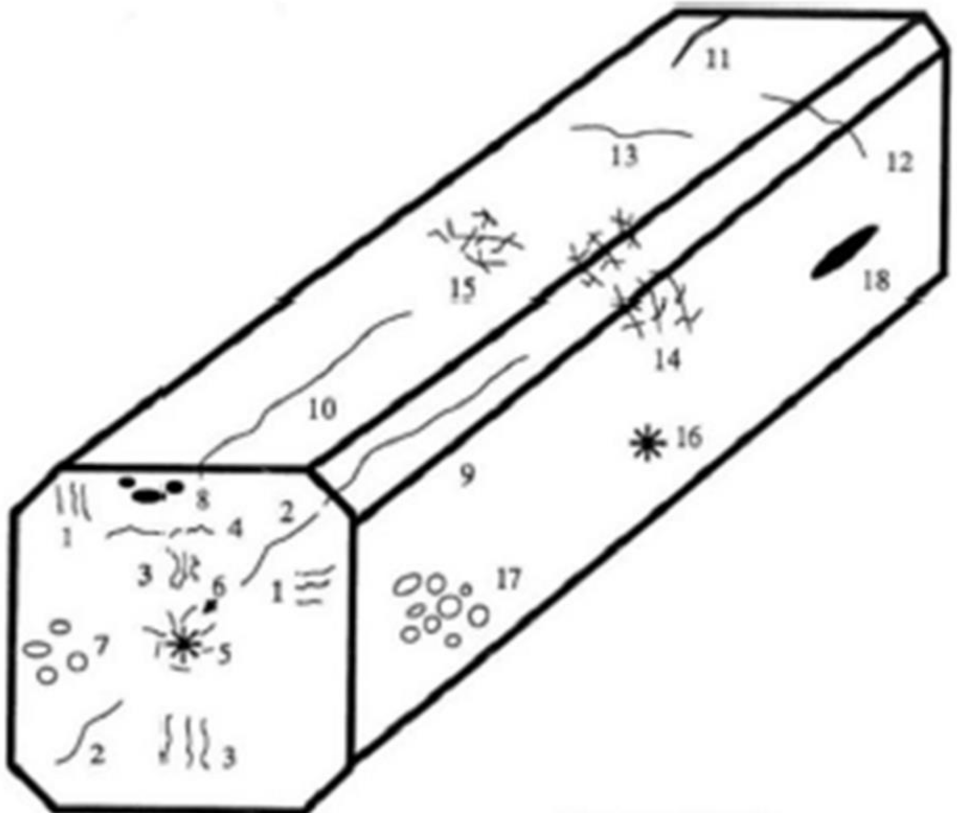


Bellet, Michel, et al. Metallurgical and Materials Transactions A 40.11 (2009): 2705-2717. Hunt, B. Stewart, 9th ECCC, European Continuous Casting Conference, 2017, p. 620

1. Introduction

Internal and surface defect

Surface defects:

Transversal cracks

Intergranular cracks

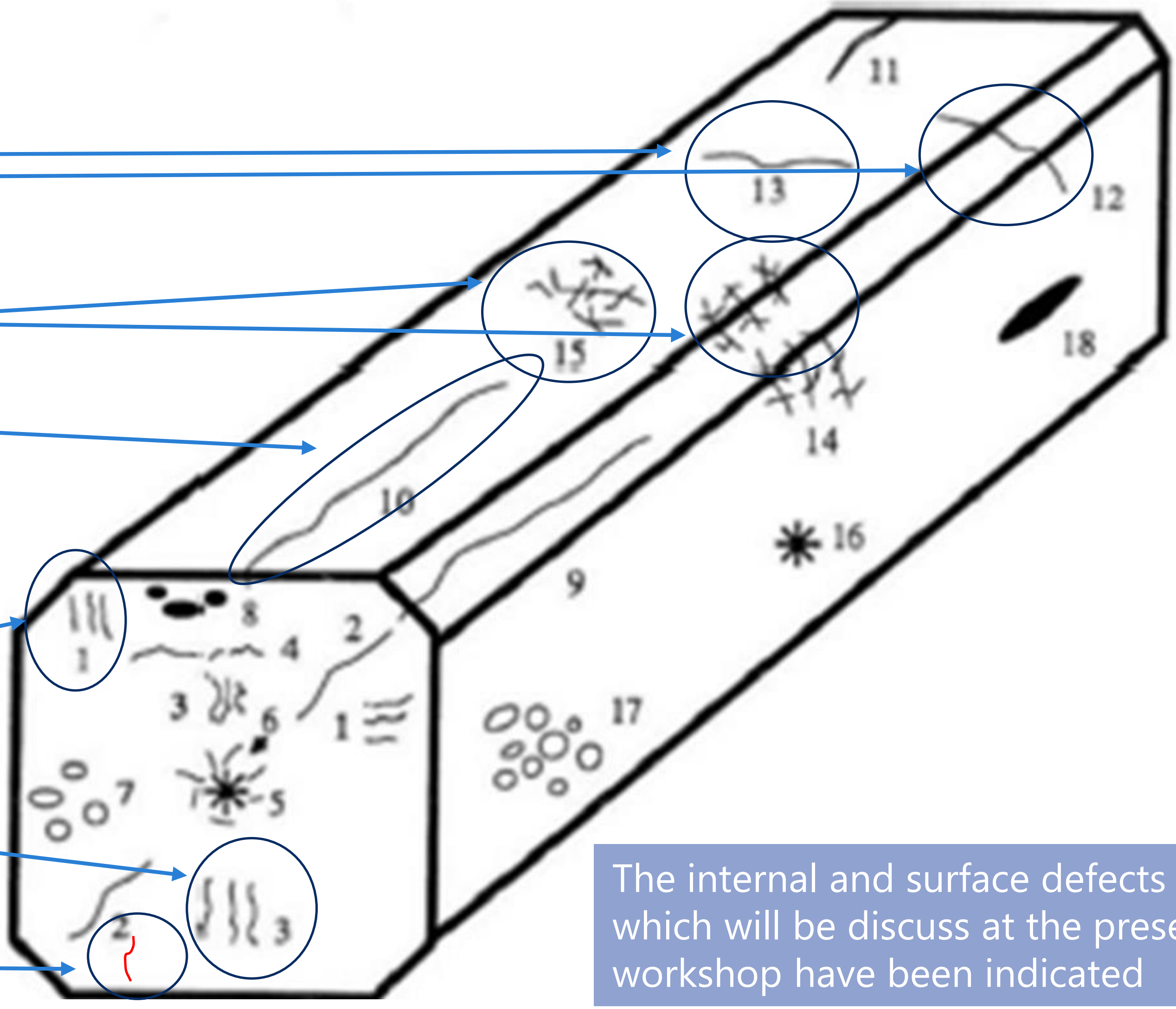
Thermal/transformation cracks

Internal segregation cracks

Off-corner cracks

Half-way cracks

Near corner cracks

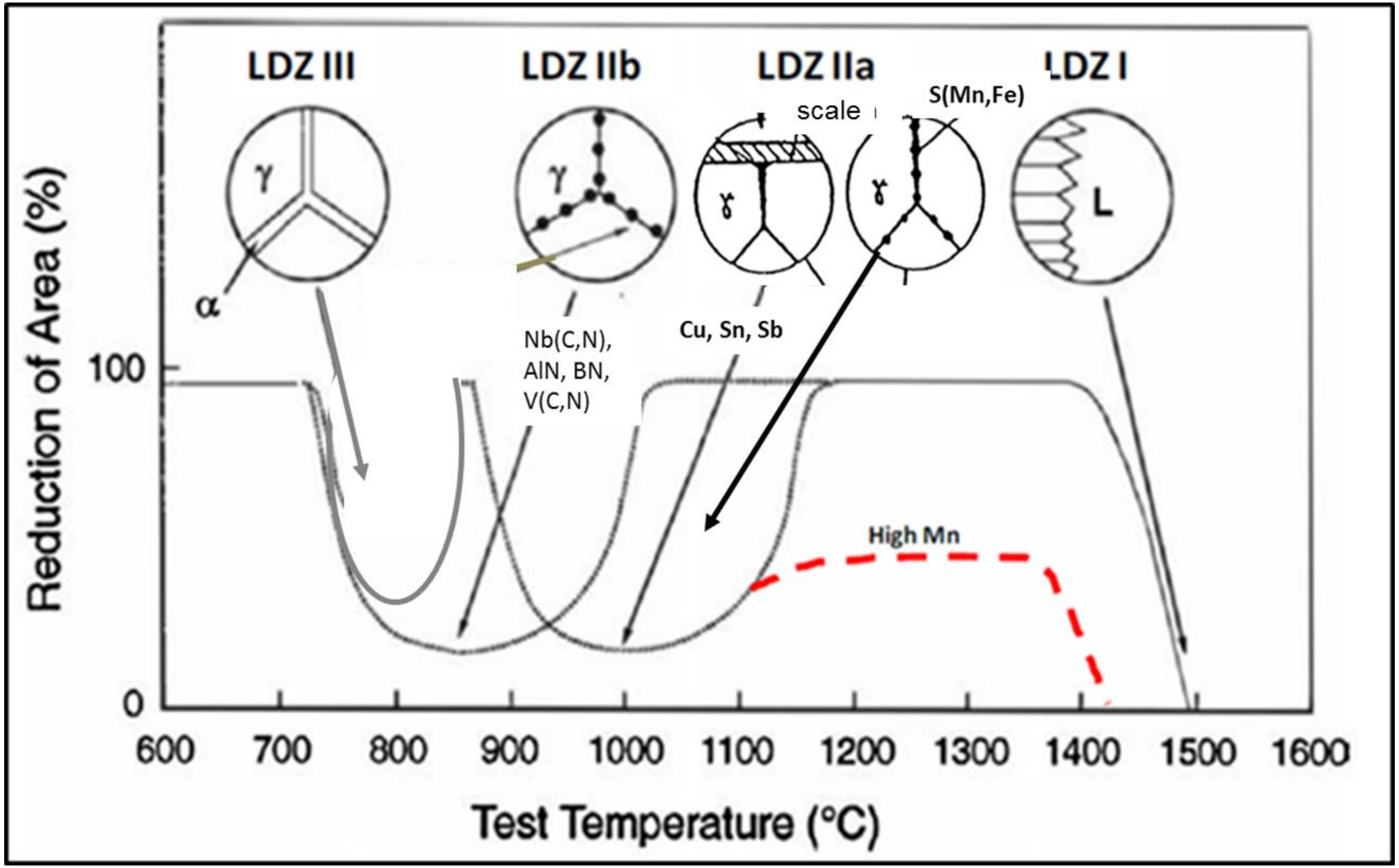


The internal and surface defects which will be discuss at the present workshop have been indicated

1. Introduction

High temperature ductility troughs

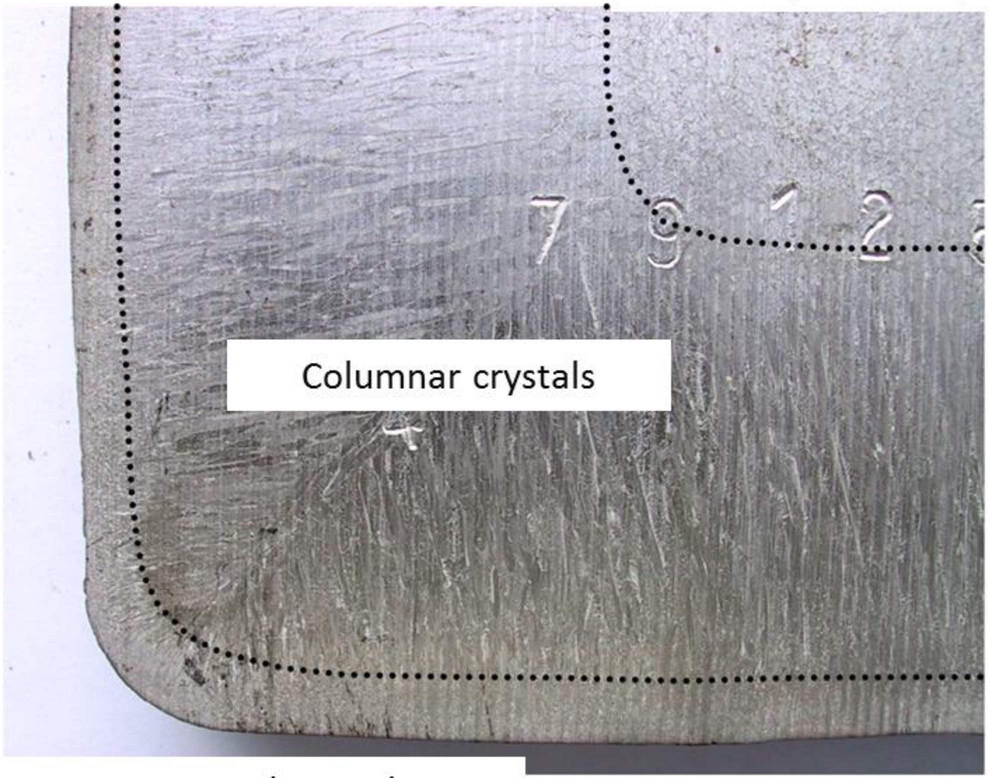
High temperature low ductility zones (LDZ) during solidification and cooling of the CC billet



2. Segregation cracking formation mechanism

2. Segregation cracking formation mechanism

- Billet internal solidification macrostructure

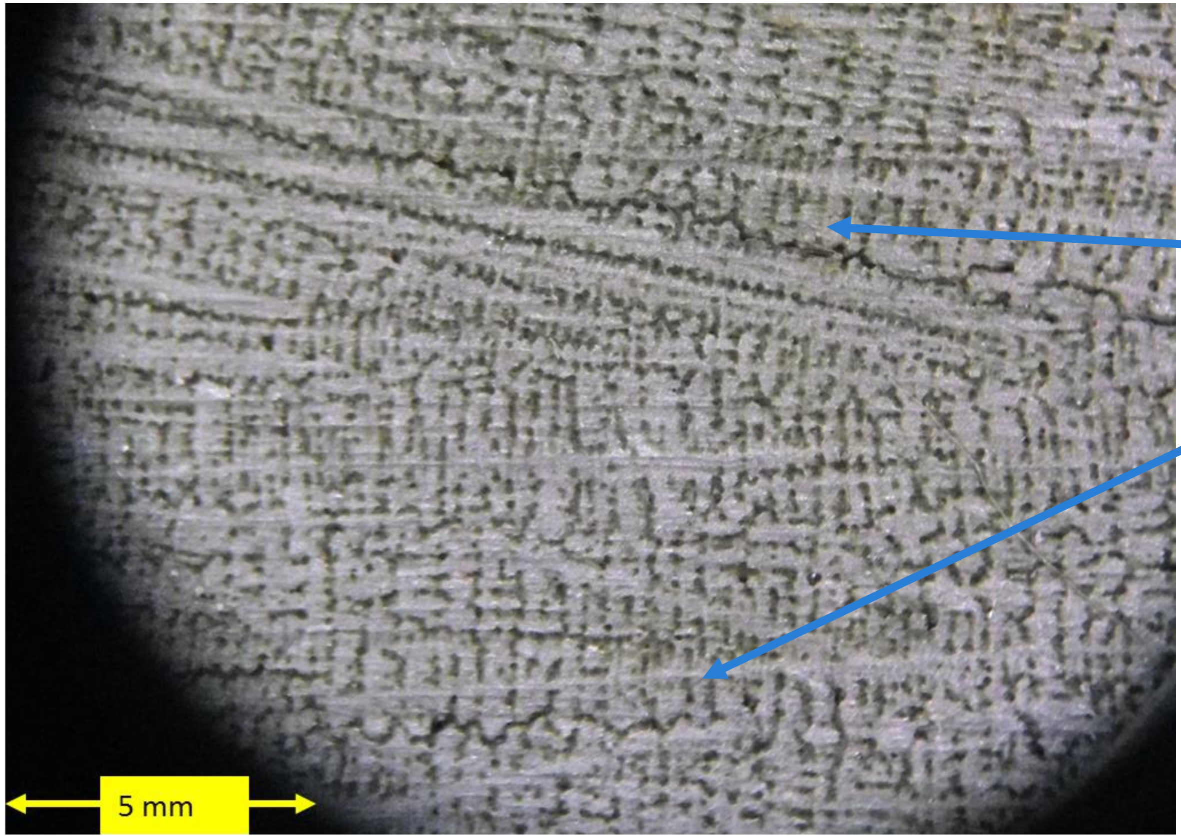


Three different solidification macrostructures can be observed in the billet at different distances to the billet surface. Segregation cracks develop in the columnar zone.

2. Segregation cracking formation mechanism

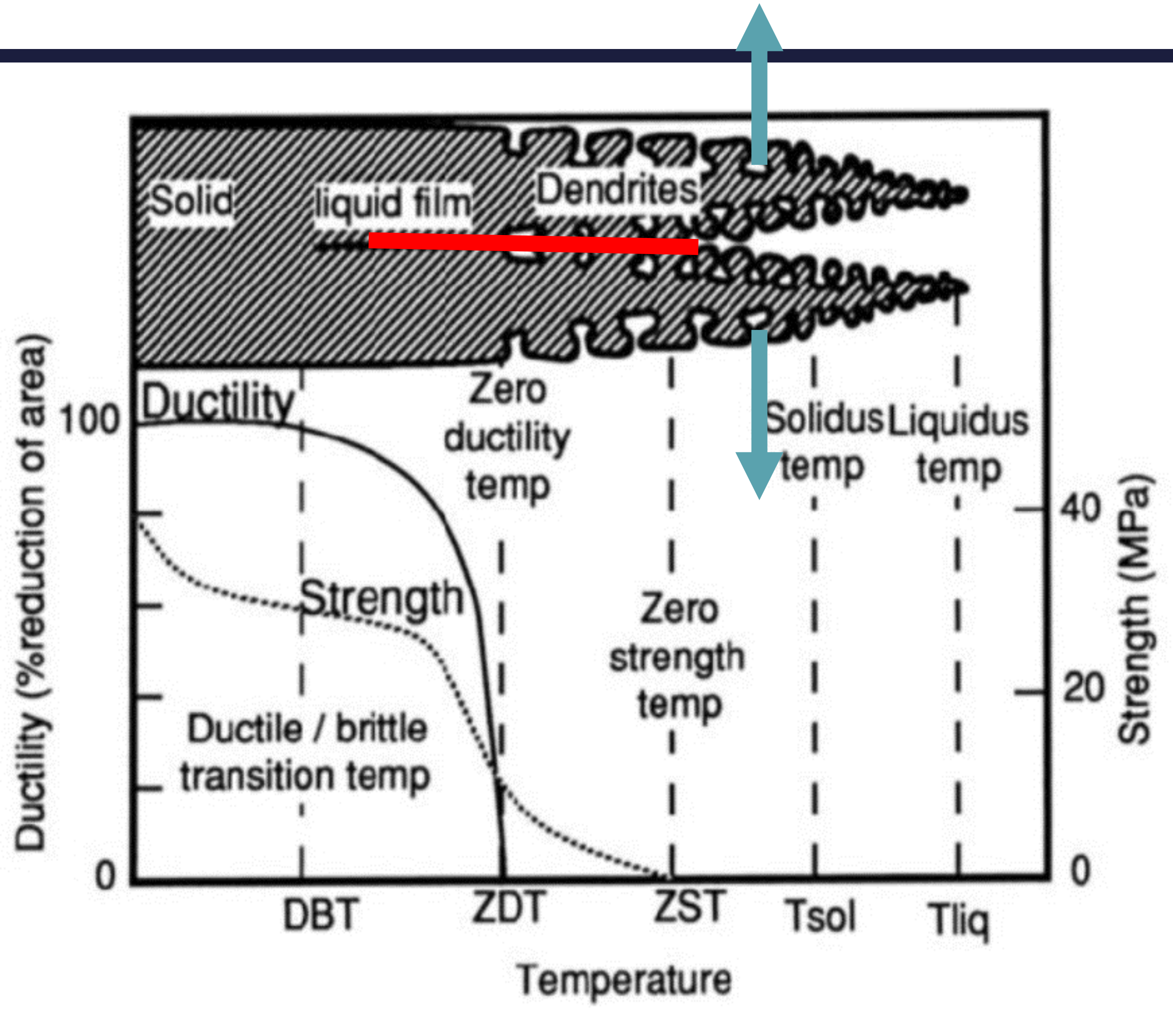
18NiCrMo5E 185 mm billet.

Crystal columnar growth area. Distance to billet surface: 60 mm.



Hot acid etching of a billet transversal sample reveal the presence of segregation cracks between dendrites.

2. Segregation cracking formation mechanism



R. Pierer and C. Bernhard. La revue de Metallurgie-CIT, Fevrier, 2007, 72-83

ZST: Zero Strength Temperature
ZDT: Zero Ductility Temperature
DBT: Ductile Brittle Temperature transition

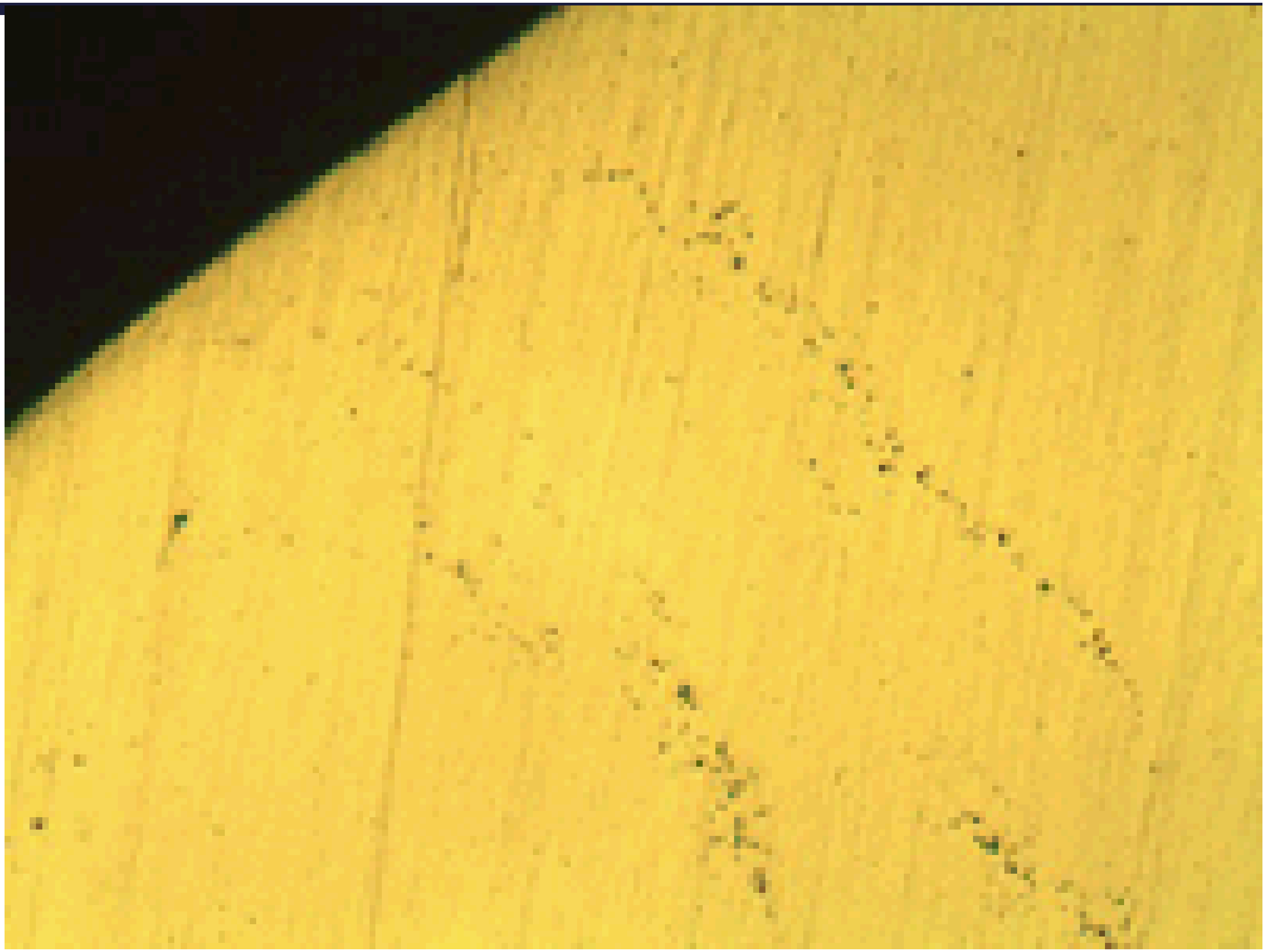
Internal segregation cracking tendency increase with:

(ZST – ZDT)

(ZST – DBT)

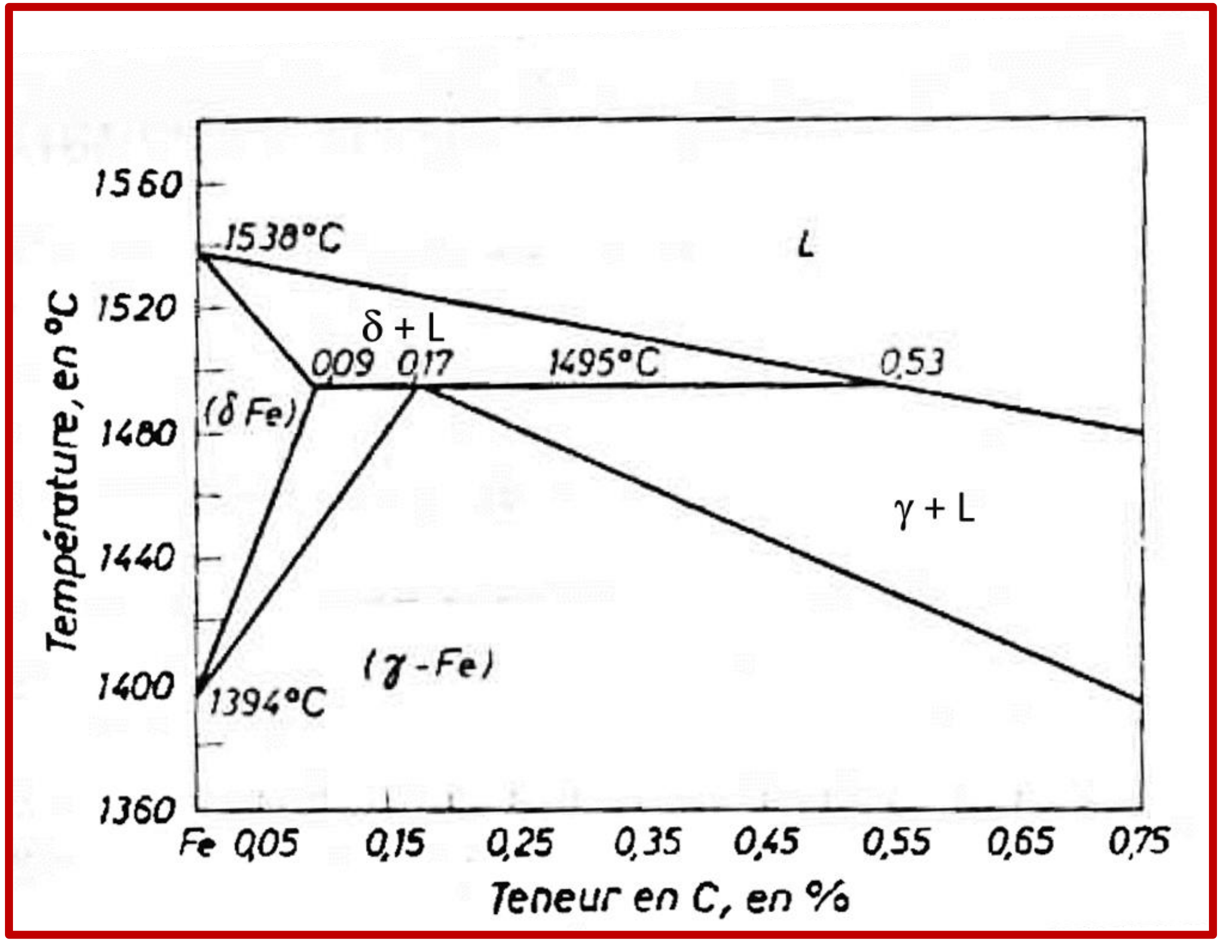
2. Segregation cracking formation mechanism

Example of the presence of segregation cracks on a rolled bar. The segregated cracks appears as a zone with a high presence of elements which segregate during solidification, mainly MnS.



2. Segregation cracking formation mechanism

Effect of highly segregated chemical elements on solidification microstructure



Partition coefficient during solidification, K, is defined by:

$$K_\delta = \frac{C_S}{C_L} = 0.09/0.53 = 0.17$$

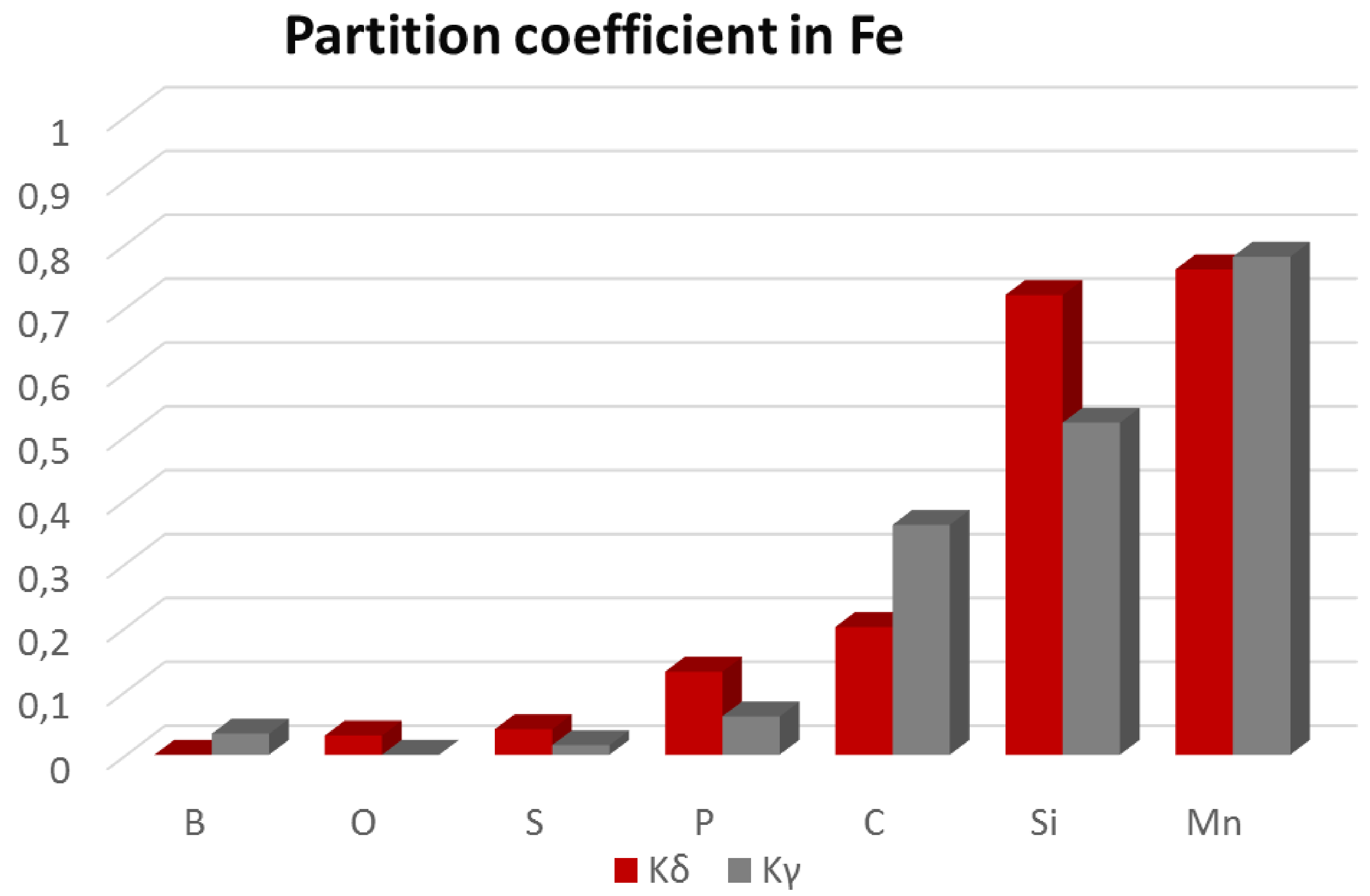
Where C_S and C_L are the solid and liquid compositions at equilibrium.

Values of the partition coefficient for sulfur are:

$$K_\delta = \frac{C_S}{C_L} = 0.05 \qquad K_\gamma = \frac{C_S}{C_L} = 0.015$$

For primary phase austenite, if the solid dissolve 0.001% S, the composition of the liquid in equilibrium will have a S content of 0.001%/0.015 = 0.66%

Effect of highly segregated chemical elements on solidification microstructure

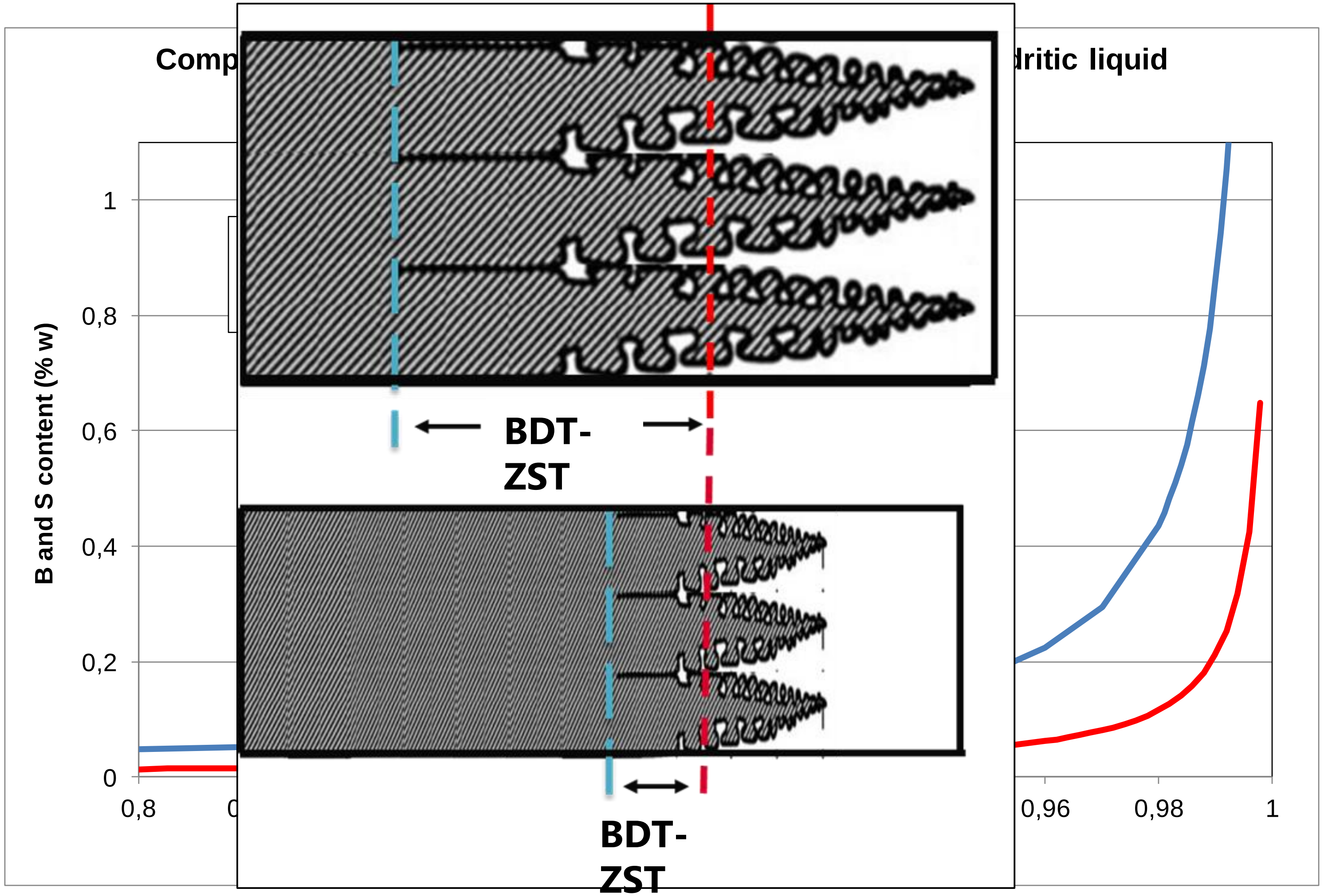


- The K coefficient of each element depends on the primary Fe solid phase.
- The chemical elements with high K values are well dissolved in the solid phase during solidification.
- The chemical elements with low K vales, are highly segregated elements, which accumulates in the residual liquid during solidification.

Effect of highly segregated chemical elements on solidification microstructure:

The concentration of the interphase liquid can be approximately calculated by the Sheill-Gulliver equation:

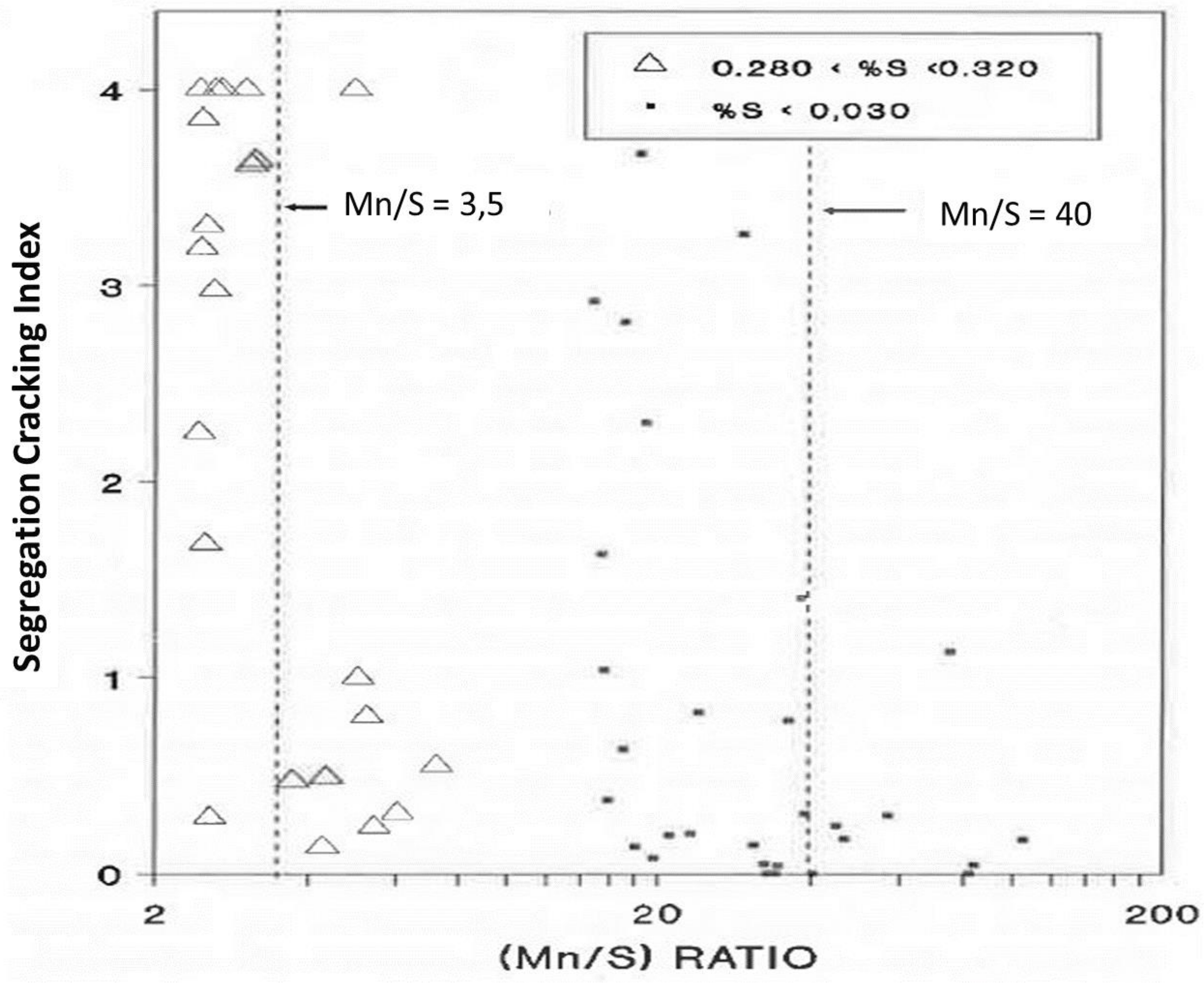
$$C_L = C_0(1 - F_S)^{(k-1)}$$



3. Influence of composition on segregation cracking: S.

3. Influence of composition on segregation cracking: S, B.

Influence of composition on segregation cracking: Sulfur



The figure shows two Mn/S ratios which are the borders between good and bad internal segregation results when casting billets. It can be seen that a change is produced in the number of billet samples with segregation cracking and that this change depends on S content of Steel:

When S: 0,300% Mn/S=3,5

When S< 0,030 Mn/S = 40.

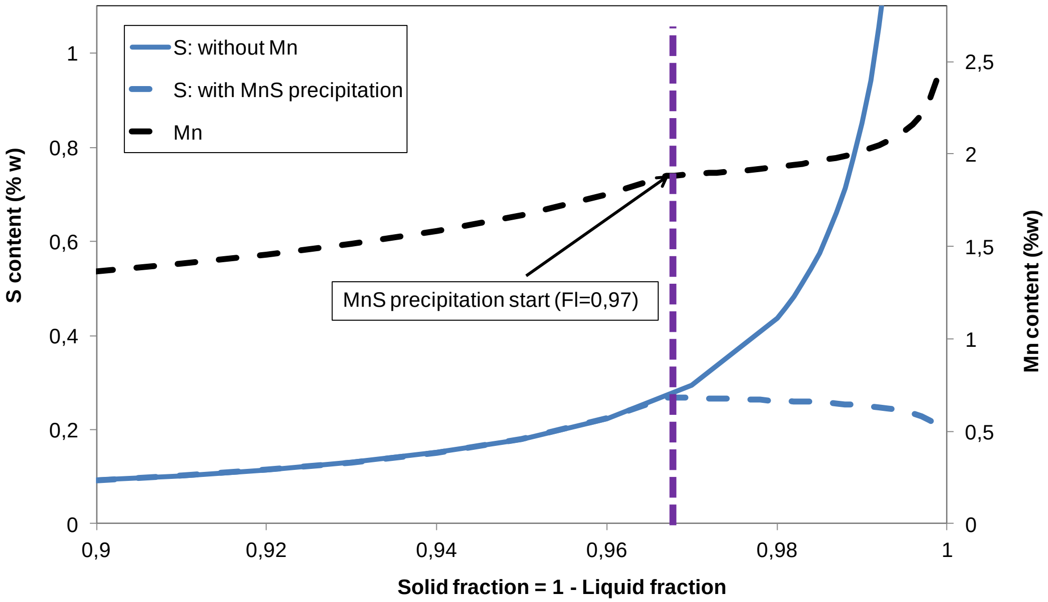
What is the cause of this behavior?

G. Alvarez de Toledo, O. Campo and E. Lainez steel research No. 6/93, 292-299

3. Influence of composition on segregation cracking: S, B.

Effect of Mn addition to a steel grade with S

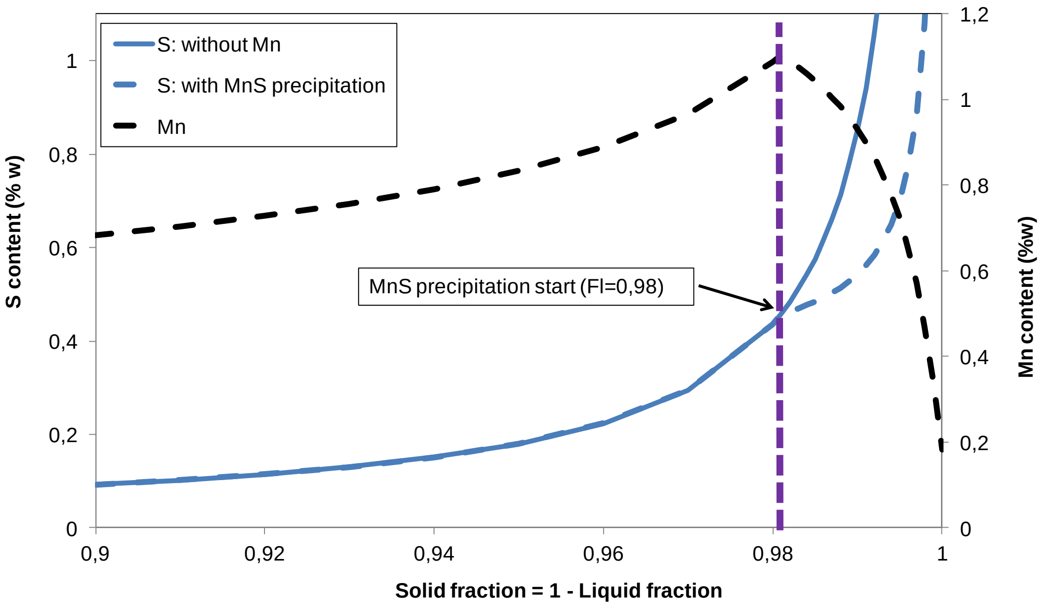
- **Case 1:** S=0,010%, Mn=0,70%



Low internal cracking tendency

$$\frac{Mn}{S} = 70$$

- **Case 2:** S=0,010%, Mn=0,35%



High internal cracking tendency

$$\frac{Mn}{S} = 35$$

Which is the Mn/S critical ratio that differentiates both behaviors?

3. Influence of composition on segregation cracking: S, B.

3. Influence of composition on segregation cracking: Sulfur

- $\left(\frac{Mn}{S}\right)_c$ **calculation**

$$\left(\frac{\mathrm{Mn}}{\mathrm{S}}\right)_{\mathrm{C}} = 1{,}345 \cdot \mathrm{S}^{-0{,}7934}$$

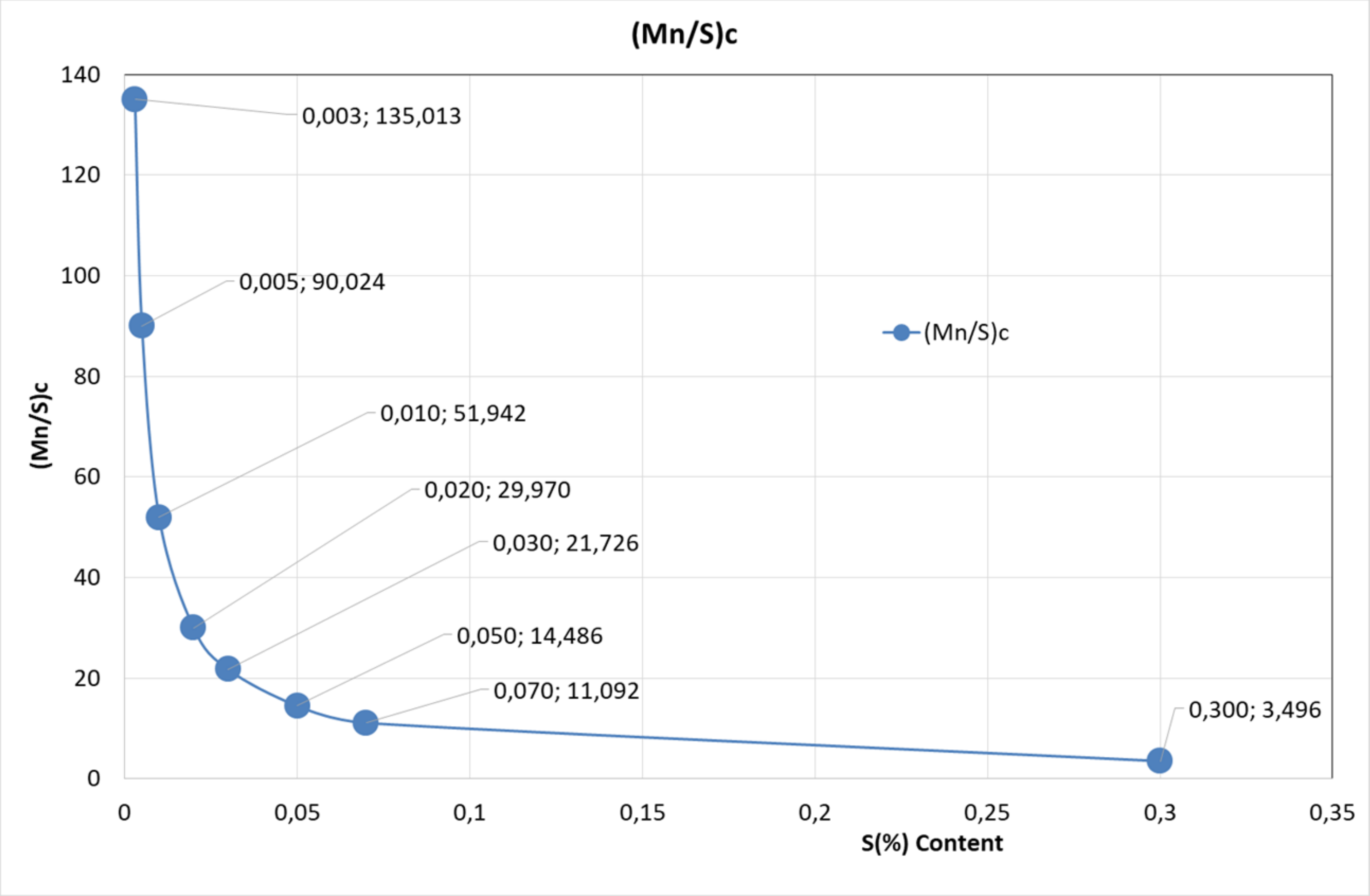
Depends only on the S content of the Steel.

- **MSC coefficient**

MSC (**M**angannese **S**ulfur **C**ritical) coefficient is defined as

$$\mathrm{MSC} = \frac{(\mathrm{Mn/S})_{\mathrm{steel}}}{(\mathrm{Mn/S})_{\mathrm{C}}}$$

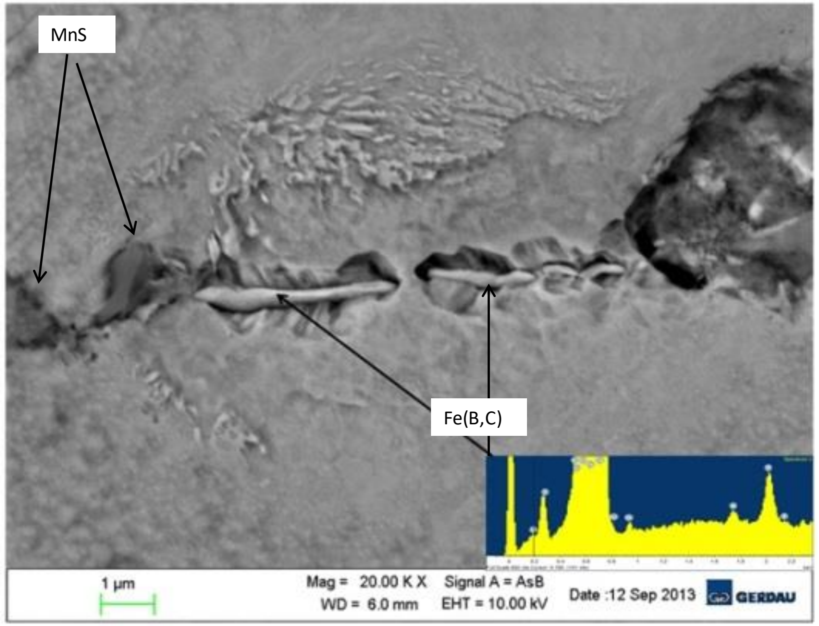
G. Alvarez de Toledo, O. Campo and E. Lainez
steel research No. 6/93, 292-299



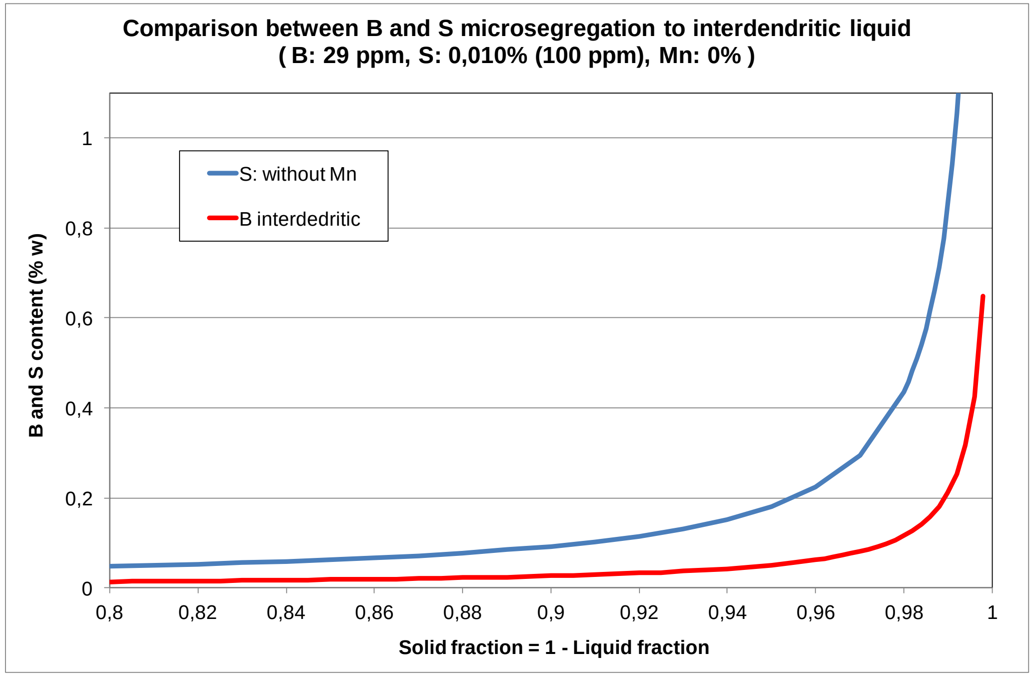
3. Influence of composition on segregation cracking: S, B.

3. Influence of composition on segregation cracking: Boron

Boron steel grades have a high tendency to form low melting interdendritic liquid



38B3E Steel grade



$$C_L = C_0(1 - F_S)^{(k-1)}$$

The boron rich interdendritic liquid solidifies at a temperature around 1.150ºC.

Is it possible to counteract the interdendritic segregation of B?

Steel grades: 38B3E, 30MnCrB5E…

The interdendritic segregation of S can be counteracted by Mn. However it is not known any chemical element which could react with B in the interdendritic liquid.

4. Internal segregation cracking classification and their causes

4. Internal segregation cracking classification

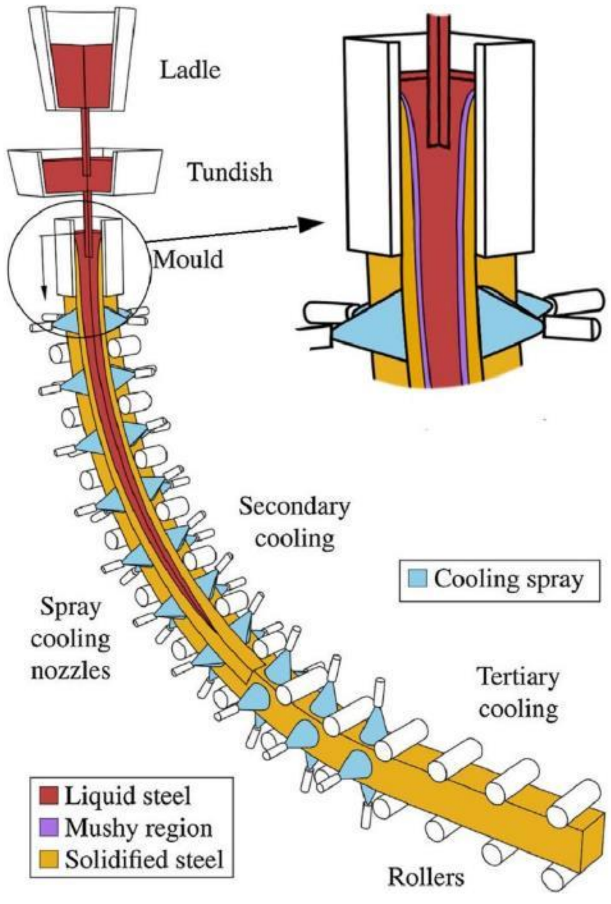
Susceptible chemical compositions

Stress at the solid shell

Segregation cracks

Depending on stress location

1. Half-way cracks
2. Off-corner cracks
3. Near corner cracks

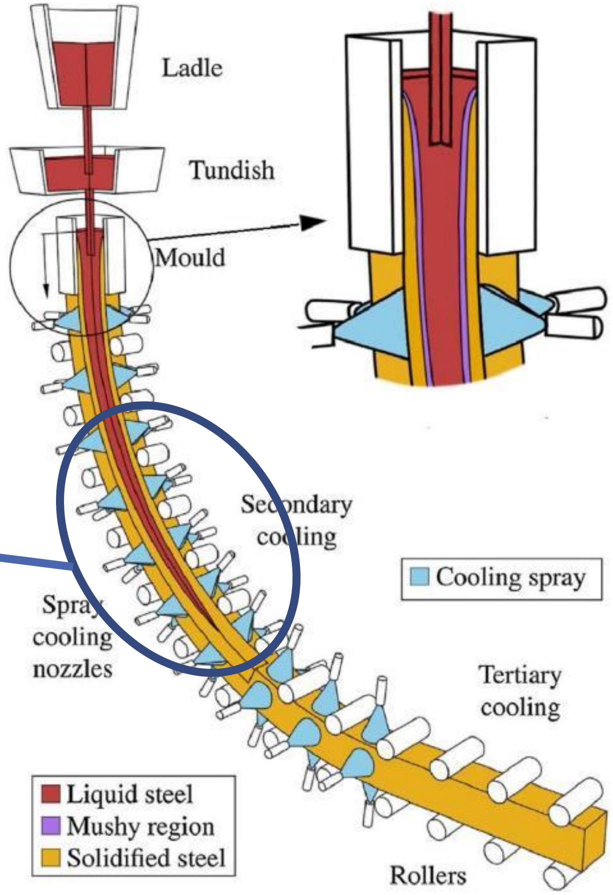


Credits: *Klimes and Stetina*

4. Internal segregation cracking classification

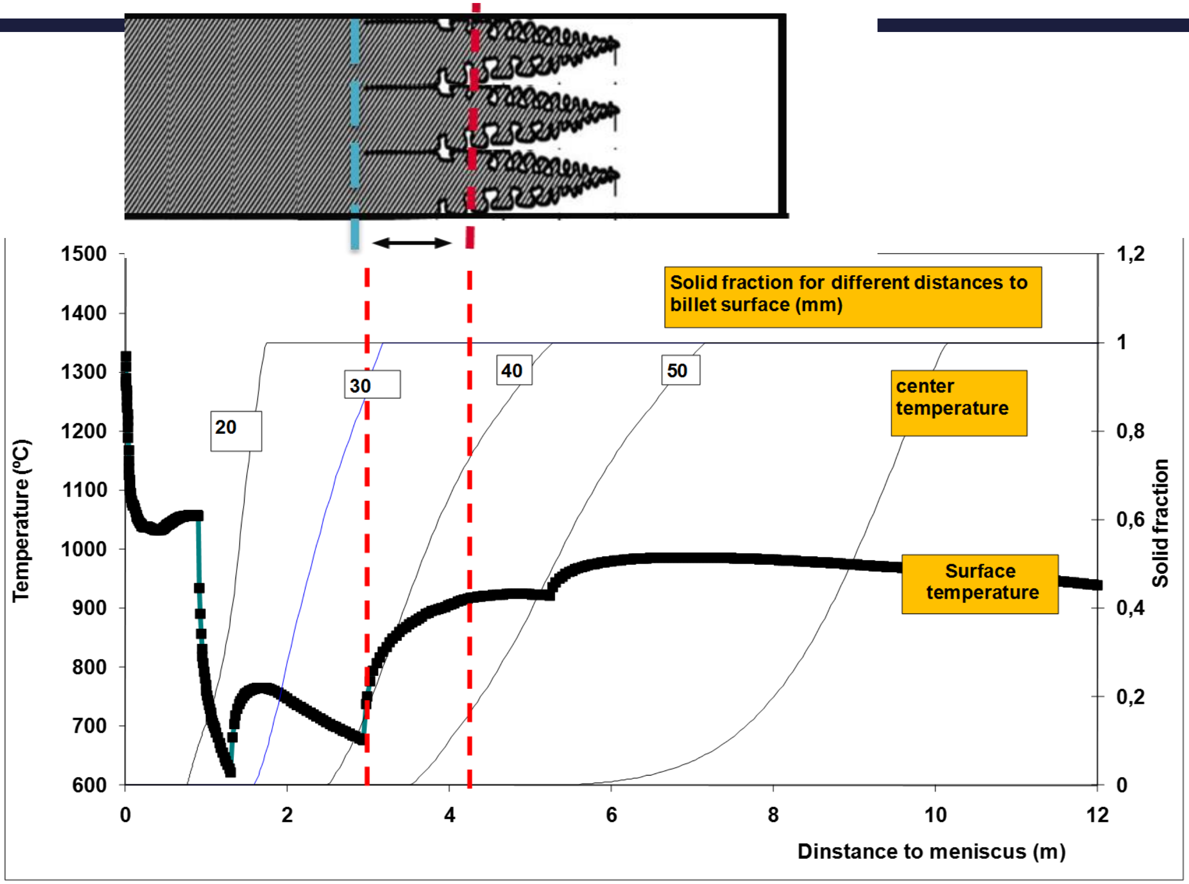
Half-way cracks.

High carbon
Steel grade.
MSC<1



4. Internal segregation cracking classification

Half-way cracks.

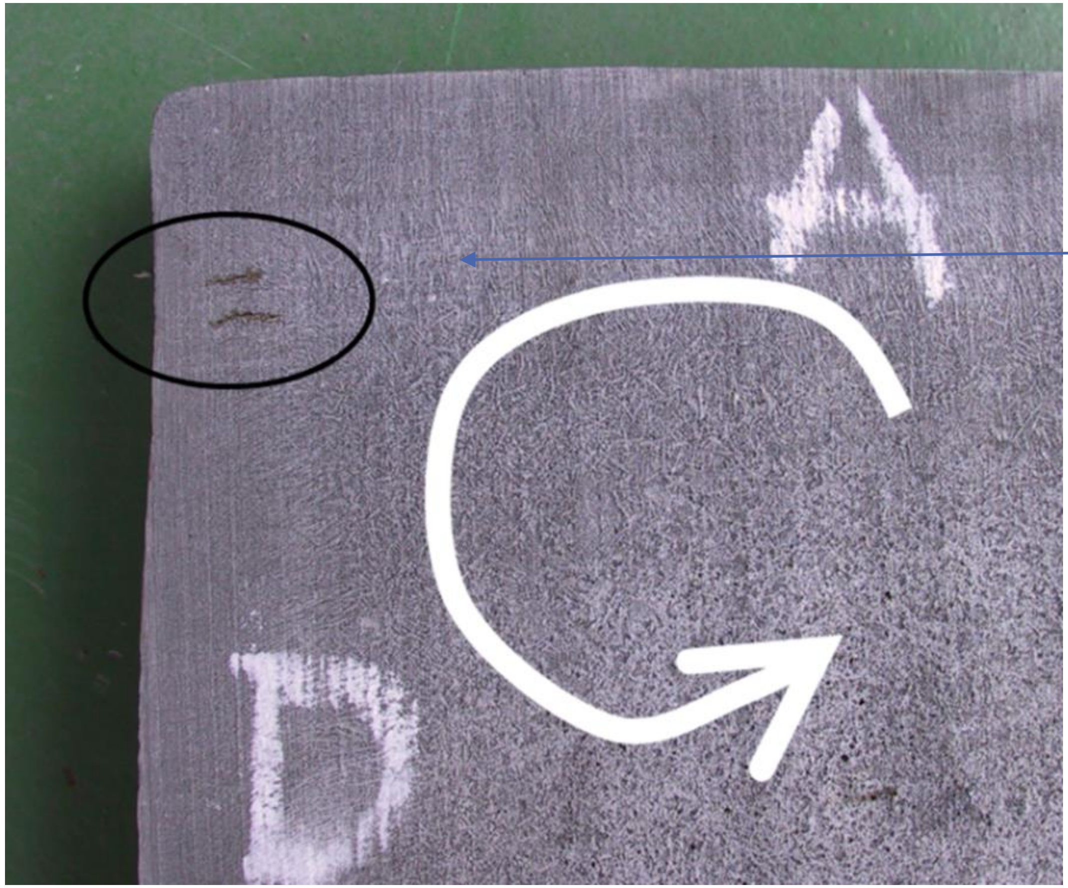


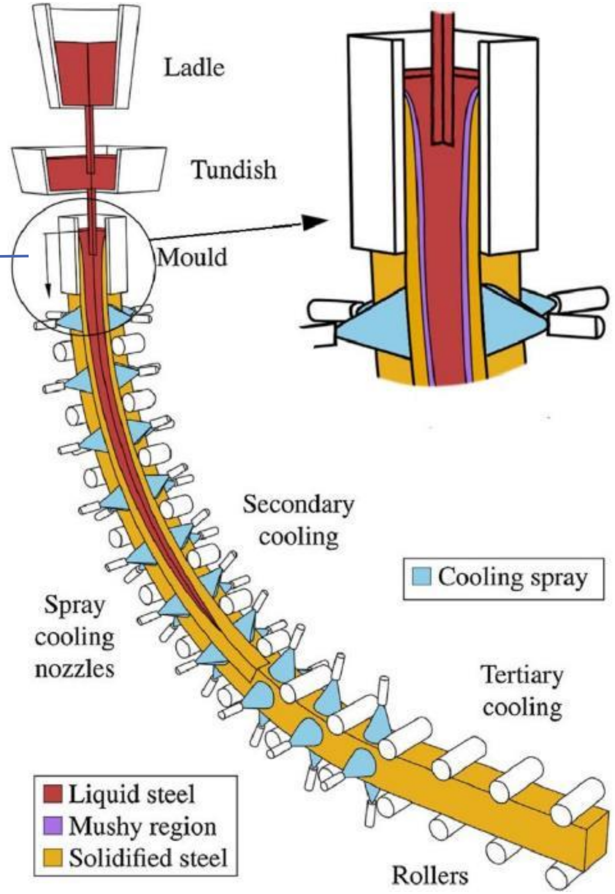
DISTEMP program calculation of the temperature and solid fraction for different distances to the billet Surface. The water cooling intensity at secondary cooling Zone II is too high, and at the transition between Zones II and III a big surface reheating takes place, leading to half-way cracking. The calculated billet depth when the reheating occurs, 30 mm, corresponds to the depth for the observed cracking.

4. Internal segregation cracking classification

2. Off-Corner cracks

Off-corner cracks are situated at the near billet corner, and also near the billet surface: billet depth between 5 and 12 mm.



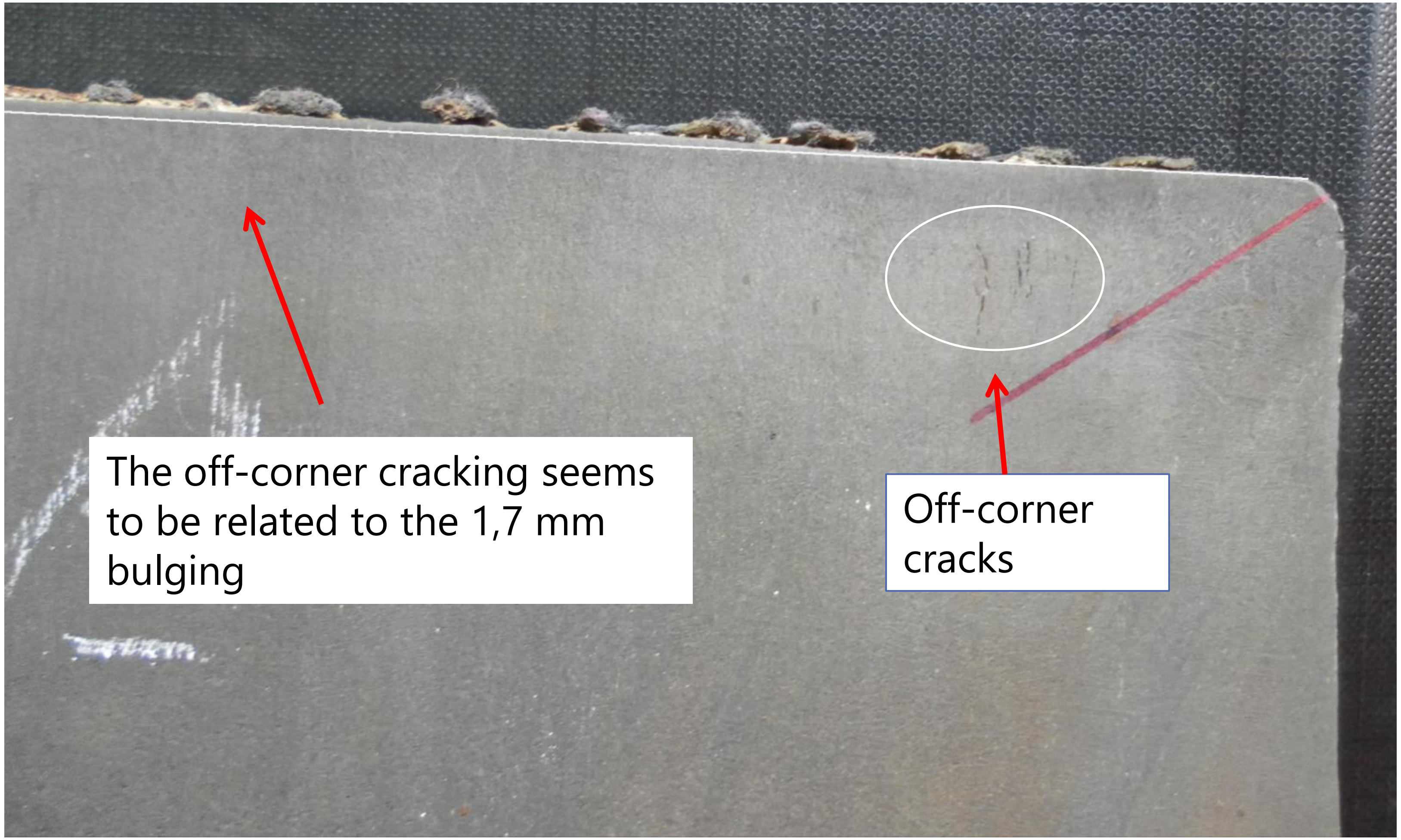


4. Internal segregation cracking classification

2. Off-Corner cracks

Off-corner cracks are situated at the near billet corner, and also near the billet surface: billet depth between 5 and 12 mm.

Photograph of a part of a 185 mm billet, showing the billet profile and off-corner cracking.



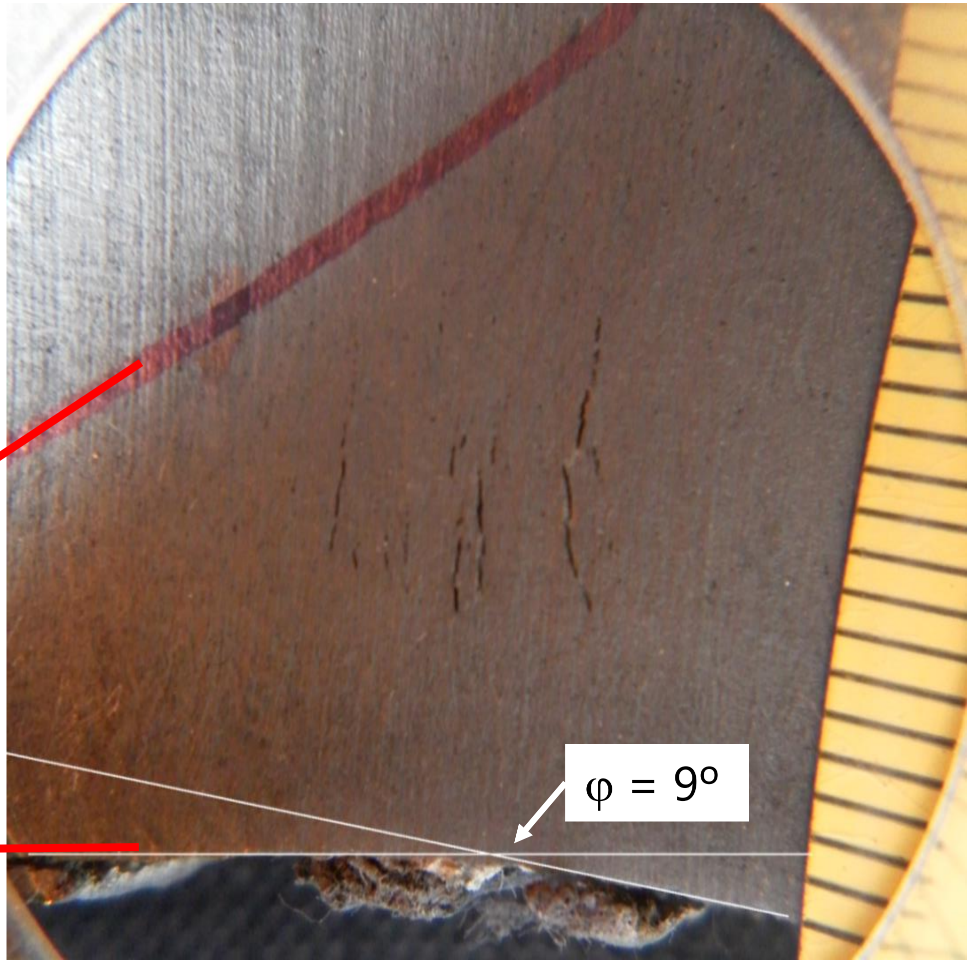
4. Internal segregation cracking classification

2. Off-Corner cracks

The off-corner cracks are situated at the hinging point of the billet surface .

The cracking is produced at 5-12 mm depth.

Billet corner



4. Internal segregation cracking classification

2. Off-Corner cracks

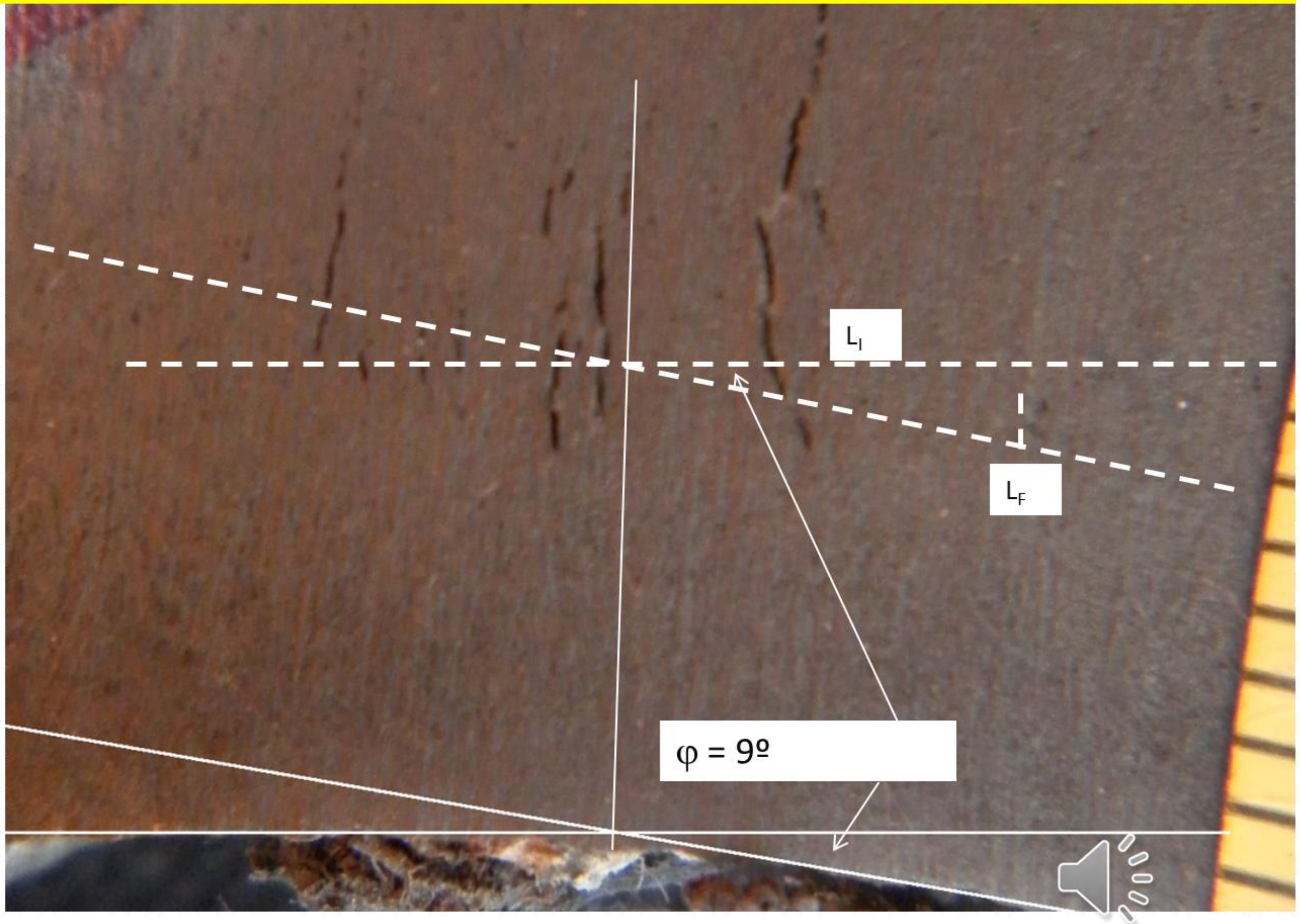
Strain at cracking position:

$\varepsilon = (L_F - Li)/Li*100 = (1/\cos(\phi)-1)*100$

$\varepsilon = 1{,}4\%$

Laboratory tests have shown that cracking at the solidifying front is produced when strain is higher than 0.5%: $\varepsilon > 0{,}5\%$

Strain calculation at the place where off-corner cracks are detected:



4. Internal segregation cracking classification

2. Off-Corner cracks

Off-corner cracking major causes

a) Differences in the mould cooling among billet faces.

b) Too thin billet solid shell at the exit of the mould.

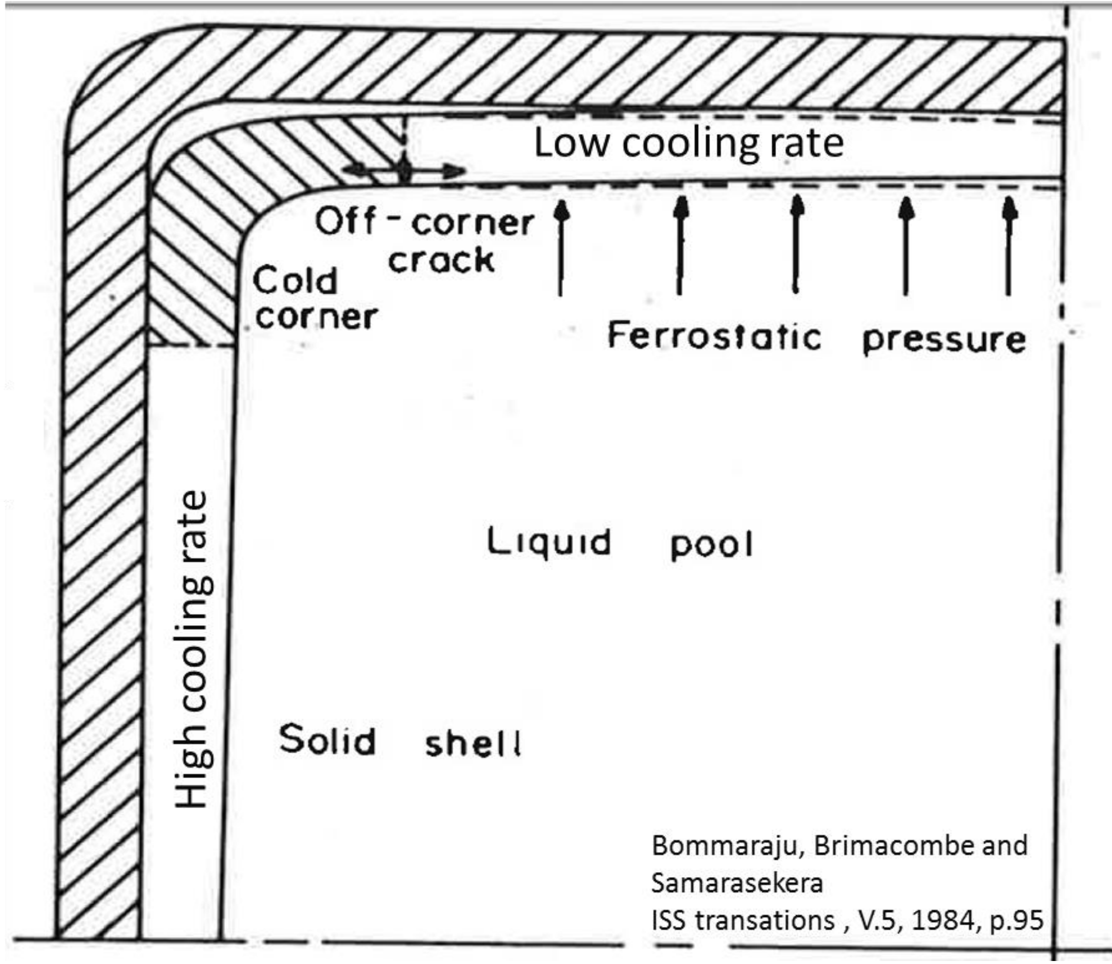
c) Too big solid shell/mold interaction.

2. Off-Corner cracks

Off-corner cracking major causes

Differences in the mould cooling among billet faces

- High cooling of one billet face with the related temperature decrease and shrinkage.
- Billet/mould loss of contact in the adjacent billet face. Bulging of this face.



Bommaraju, Brimacombe and Samarasekera
ISS transations , V.5, 1984, p.95

4. Internal segregation cracking classification

2. Off-Corner cracks

Off-corner cracking major causes

Too thin billet solid shell at the exit of the mould.

Heat 568, 34CrNiMo6EV. 185 mm billet.

Sample: 68 end of casting
Casting speed: 1.73 m/min
High billet/mould friction force
Rhomboidity= 1.0 mm
bulging Left face: 1.5 mm
Bulging in the right face: 2.5 mm
6.5 mm depth OCC

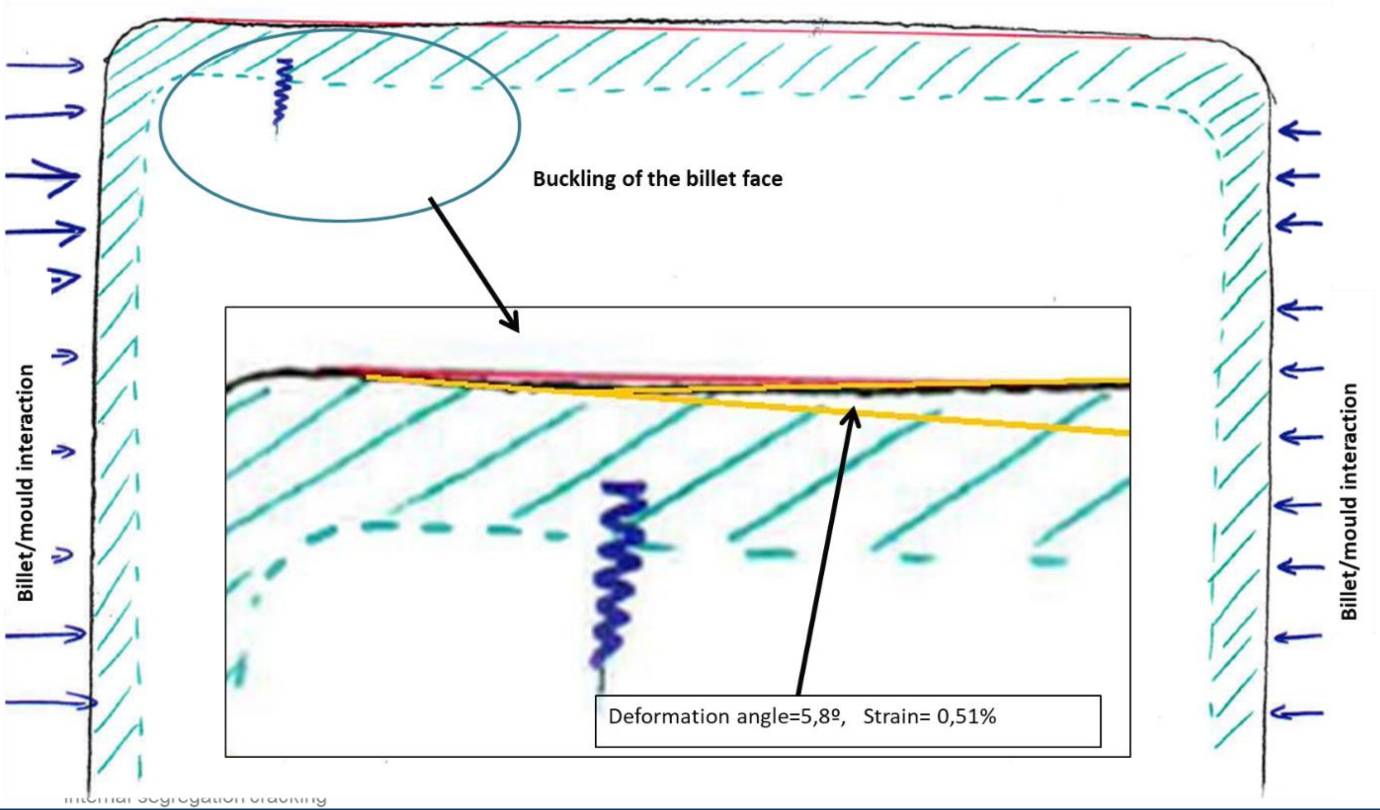
Due to the high casting speed the solid shell, thickness at the end of the mould is too thin and a bulging is produced in three of the billet faces with the related off-corner cracking.

4. Internal segregation cracking classification

2. Off-Corner cracks

Off-corner cracking major causes

Off-corner cracking major causes: too big solid shell/mould interaction



Too much interaction on two billet faces, and the buckling of the adjacent billet face. Causes of the large interaction/friction:

- High casting speed
- High mould taper
- Mould wear at the meniscus.

4. Internal segregation cracking classification

2. Off-Corner cracks

Means to avoid off-corner cracking

1. Differences in the mould cooling among billet faces:
   - Uniform copper mould cooling for the four faces .
   - CC machine alignment.
   - SEN alignment in the mould
   - Correct performance of the mould powders.
2. Too thin billet solid shell at the exit of the mould:
   - Decrease the casting speed
   - Mould paper adjustment
3. Too big solid shell/mold interaction:
   - Good copper mould conditions: nor excessive wear or deformation.
   - Tapper decrease
   - Decrease the casting speed

4. Internal segregation cracking classification

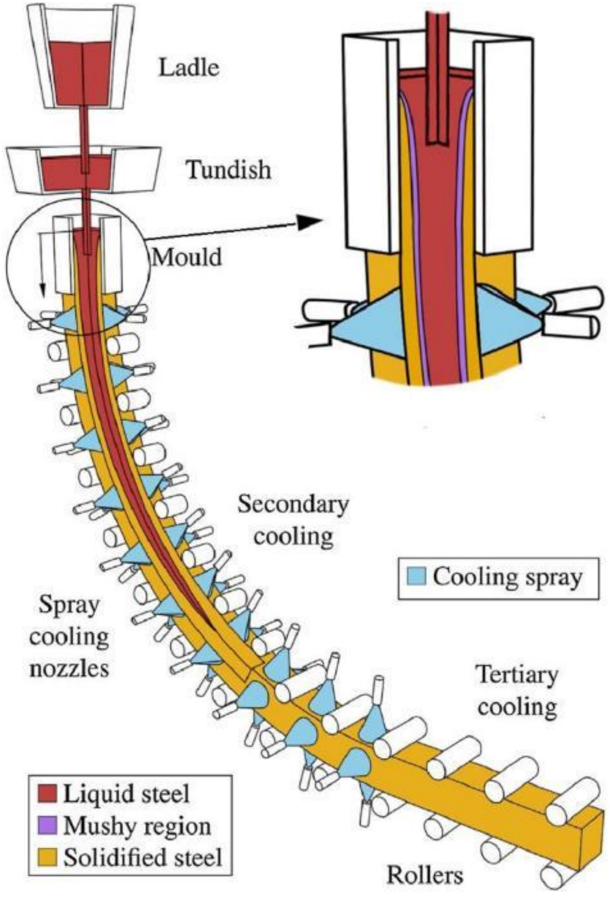
Susceptible chemical compositions

Stress at the solid shell

Segregation cracks

Depending on stress location

1. Half-way cracks
2. Off-corner cracks
3. Near corner cracks

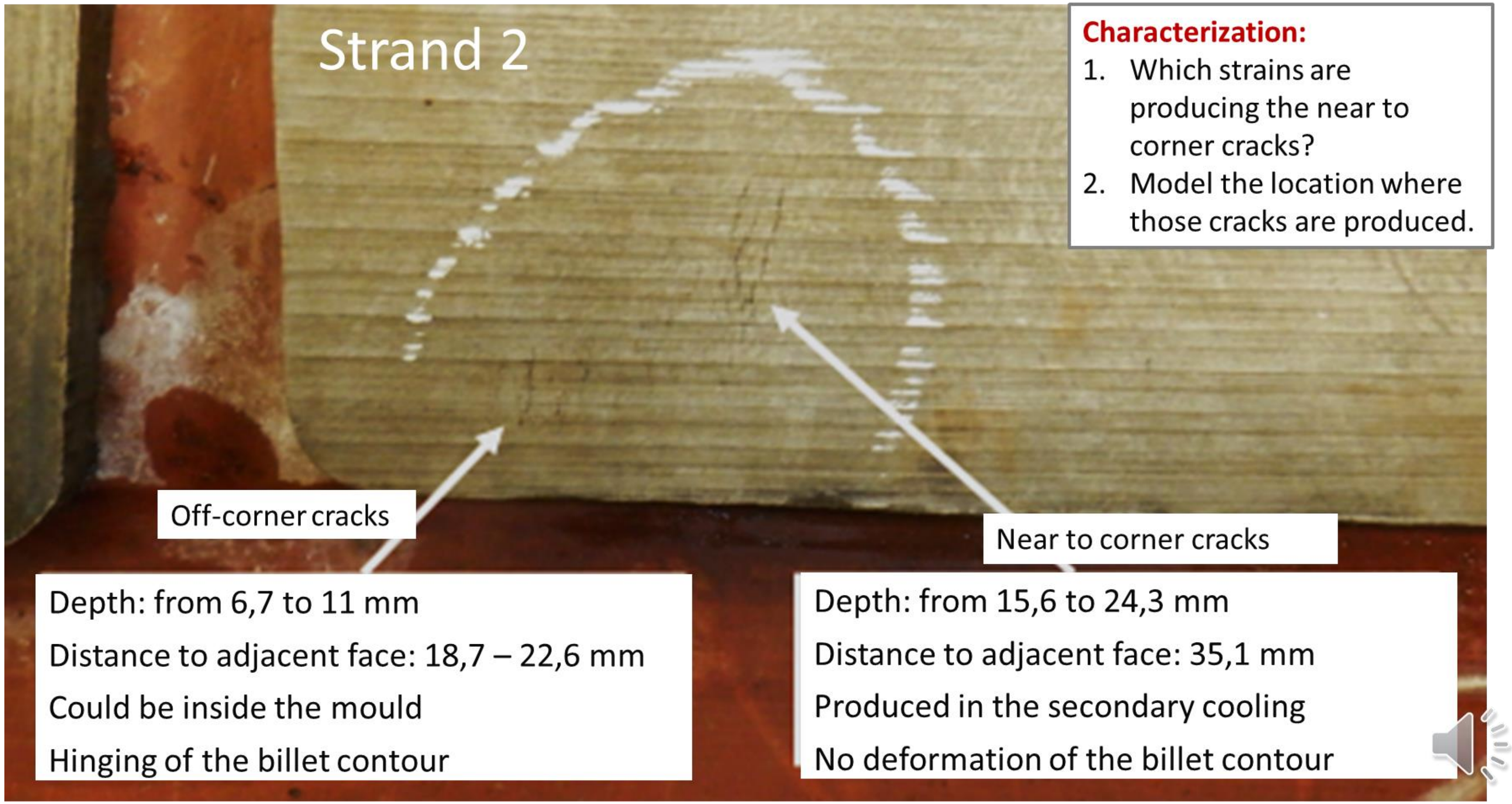


Credits: *Klimes and Stetina*

4. Internal segregation cracking classification

3. Near to corner cracking:

Practical examples: 21NiMoCr6E 240 mm billet.

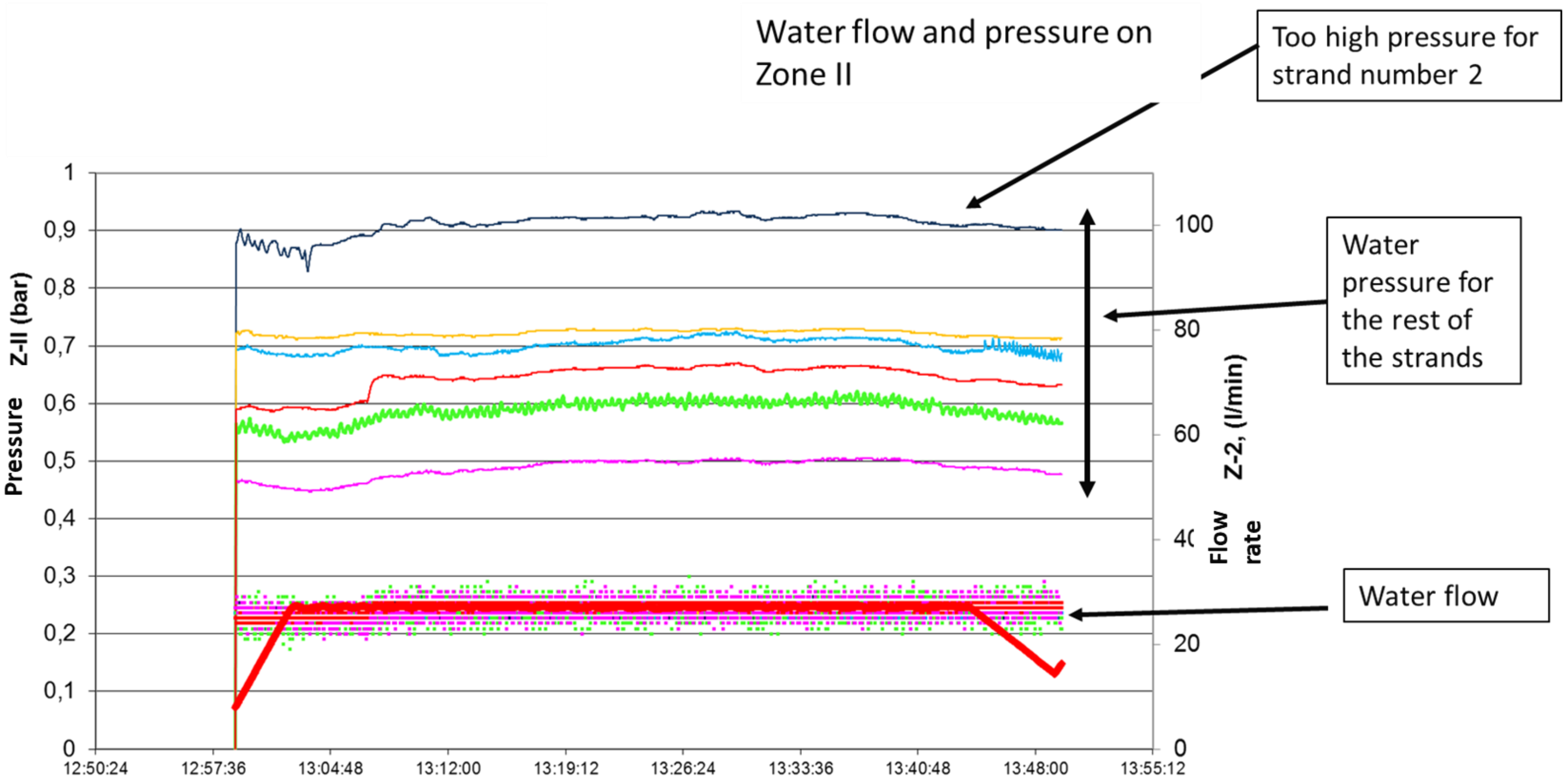


Characterization:
1. Which strains are producing the near to corner cracks?
2. Model the location where those cracks are produced.

4. Internal segregation cracking classification

3. Near to corner cracking:

Practical examples: 21NiMoCr6E 240 mm billet.

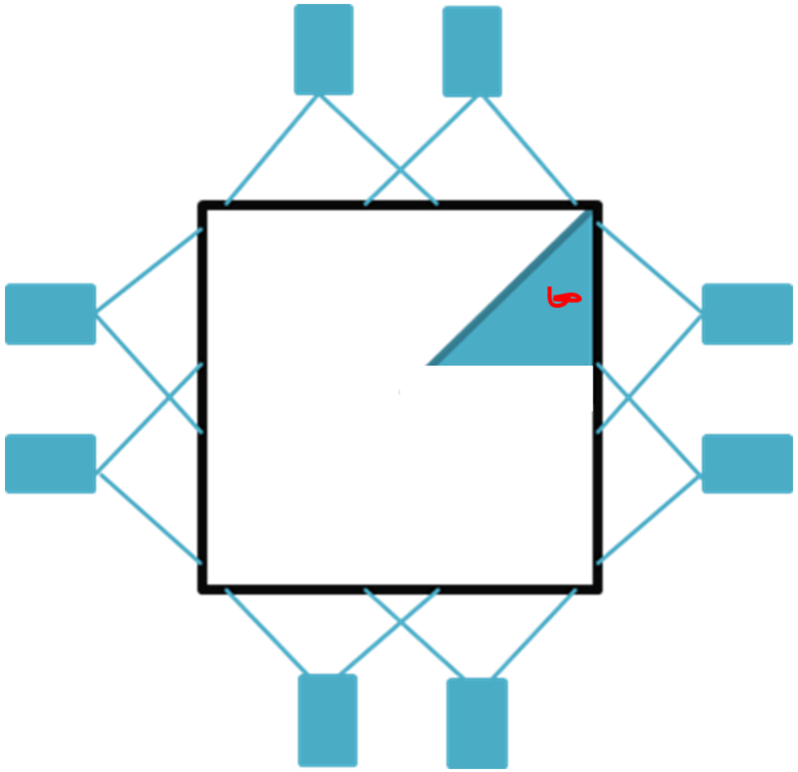


4. Internal segregation cracking classification

3. Near to corner cracking:

Practical examples: 21NiMoCr6E 240 mm billet.

- Study of the stress producing cracks



Transversal view of the Zone II secondary cooling design for the 240 mm billet.

The nozzle plugged would affect a
To less than a quarter billet area, as the one indicated in the figure.

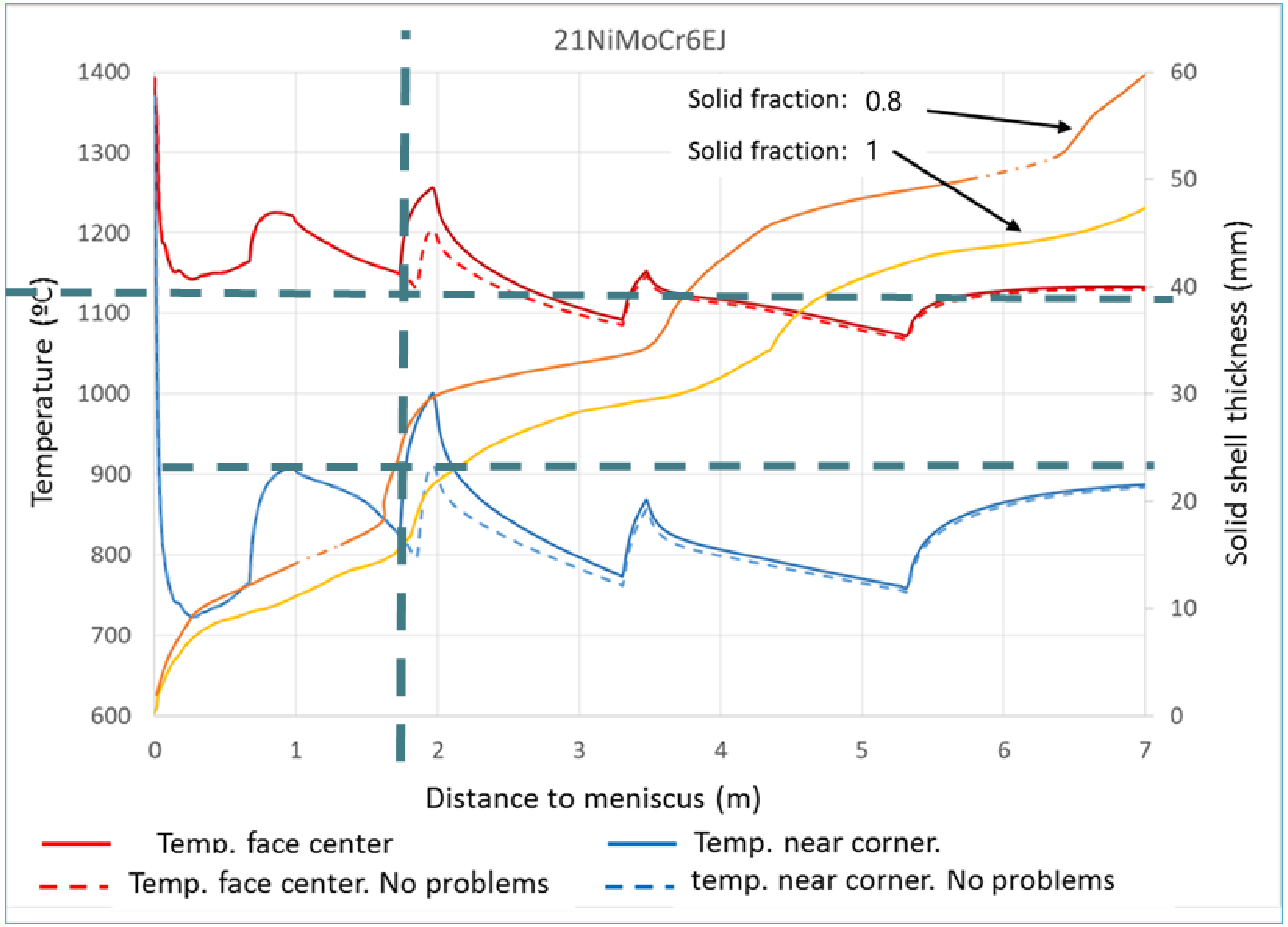
The cracks depth has been investigated with the DISTEMP program, assuming that the plugged nozzle is the last row of the Zone II. In this case, the reheating corresponding to the damaged nozzle has to be added to the reheating corresponding to the transition from Zone II and Zone III.

4. Internal segregation cracking classification

3. Near to corner cracking:

Practical examples: 21NiMoCr6E 240 mm billet.

- DISTEMP simulation



5. Conclusions

Conclusions

1. The presence of segregation cracking is related with the presence of stresses at the solidified solid shell.
2. Cracking is enhanced by a low Mn/S ratio, by the presence of boron and by the iron solid primary phase being γ.
3. The internal segregation cracks can be named by the location of billet where they are observed: Half-way cracks, off-corner cracks and near corner cracks.
4. Half way cracking is related to a wrong design of the secondary water cooling intensity, or a large gap between secondary cooling zones. Both of them producing big surface reheating.
5. Off-corner cracks are related to a non uniform solid shell formation inside the mould or a too thin solid shell thickness at the mould exit.
6. Nozzle plugging at the secondary cooling Zone I induces the formation of near corner cracks due to surface reheating. These cracks are deeper and farther from the adjacent billet face than the off-corner cracks.

THANK YOU VERY MUCH FOR YOUR ATTENTION.

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