Valcra Workshop on the influence of S and Microalloyed elements on the Surface cracking of continuous Casting Billets

Internal segregation cracking

Formation mechanism; influence of S, Mn and B on cracking. Impact of casting parameters.

Gonzalo Álvarez de Toledo and Nora Egido
5th March 2020
Process Department
Sidenor I+D

VALCRA

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3. Influence of steel chemical elements on segregation cracking: C, S, B..
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   - Off-corner cracks
   - Near corner segregation cracks
5. Conclusions

1. INTRODUCTION

1. Introduction

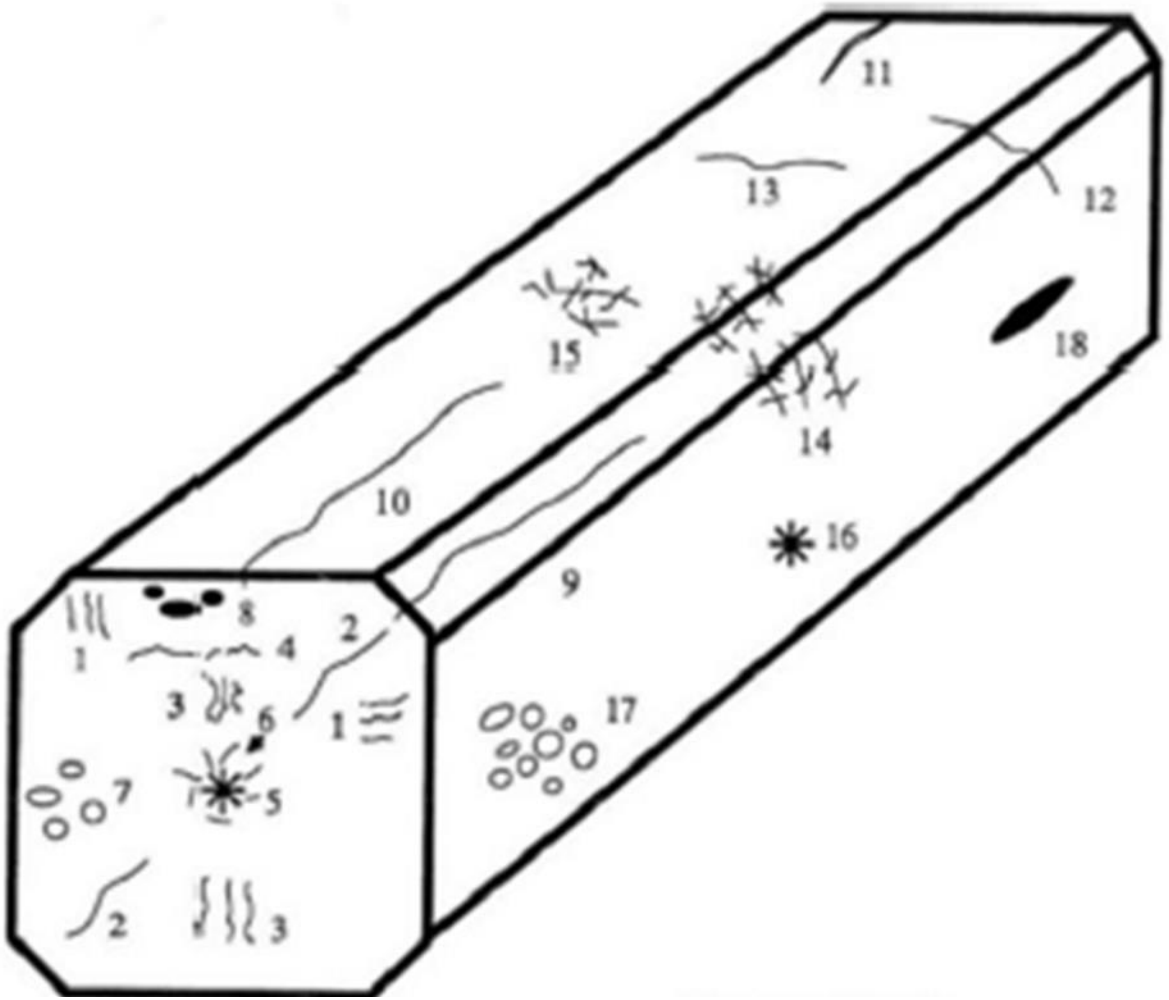
Internal and surface de

Internal defects:

1. Off-corner cracks
2. Corner cracks
3. Half-Way Crack
4. Transversal cracks
5. Star-Crack
6. Central pipe
7. Pore, blown holes
8. Powder entrapment

Surface defects:

9. Corner cracks
10. Longitudinal cracks
11. Thermal/transformation longitudinal cracks
12. Corner transversal cracks
13. Face transversal cracks
14. Intergranular cracks (corner)
15. Intergranular cracks (face)
16. Surface star cracks Start cracks
17. Pores, blow holes
18. Powder entrapment



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

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1. Introduction

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

Surface cracks:

Transversal cracks

Intergranular cracks

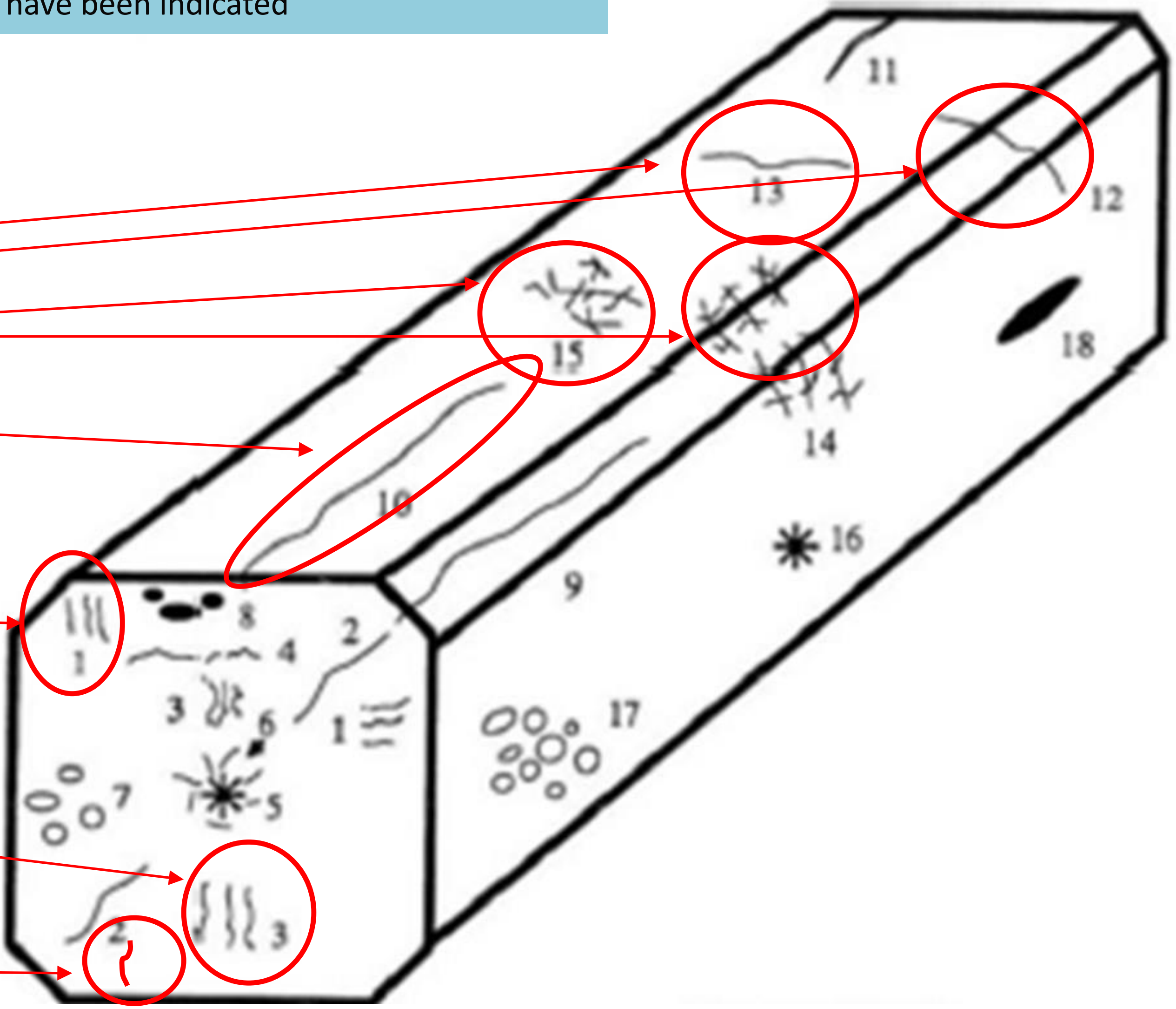
Thermal/transformation cracks

Internal segregation cracks:

Off-corner cracks

Half-way cracks

Near corner cracks



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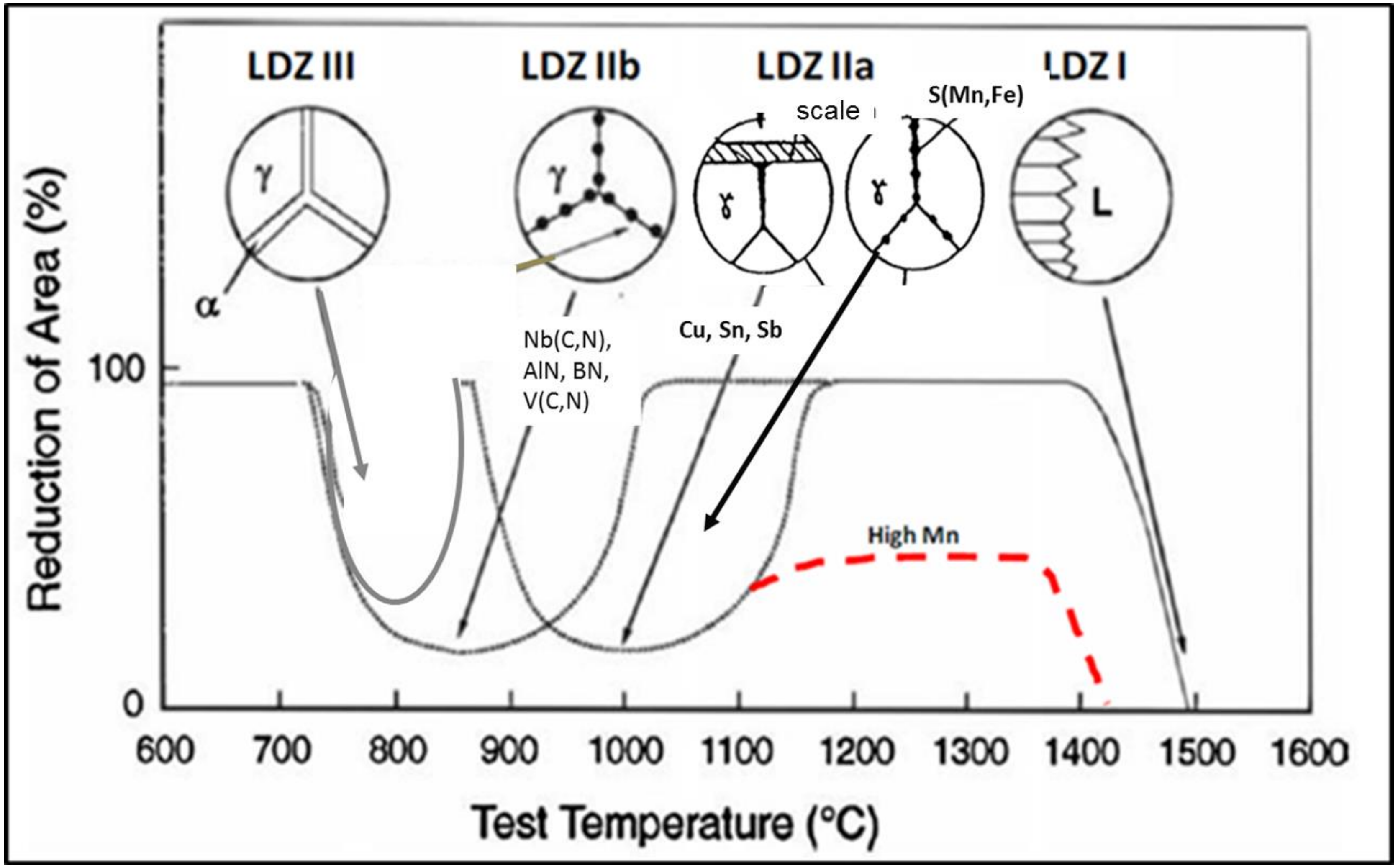
1. Introduction

High temperature ductility troughs during solidification and cooling of the CC billet



D. Crowther: Mater. Sci. Technol., 1986, vol. 2 (7), pp. 1099–105.

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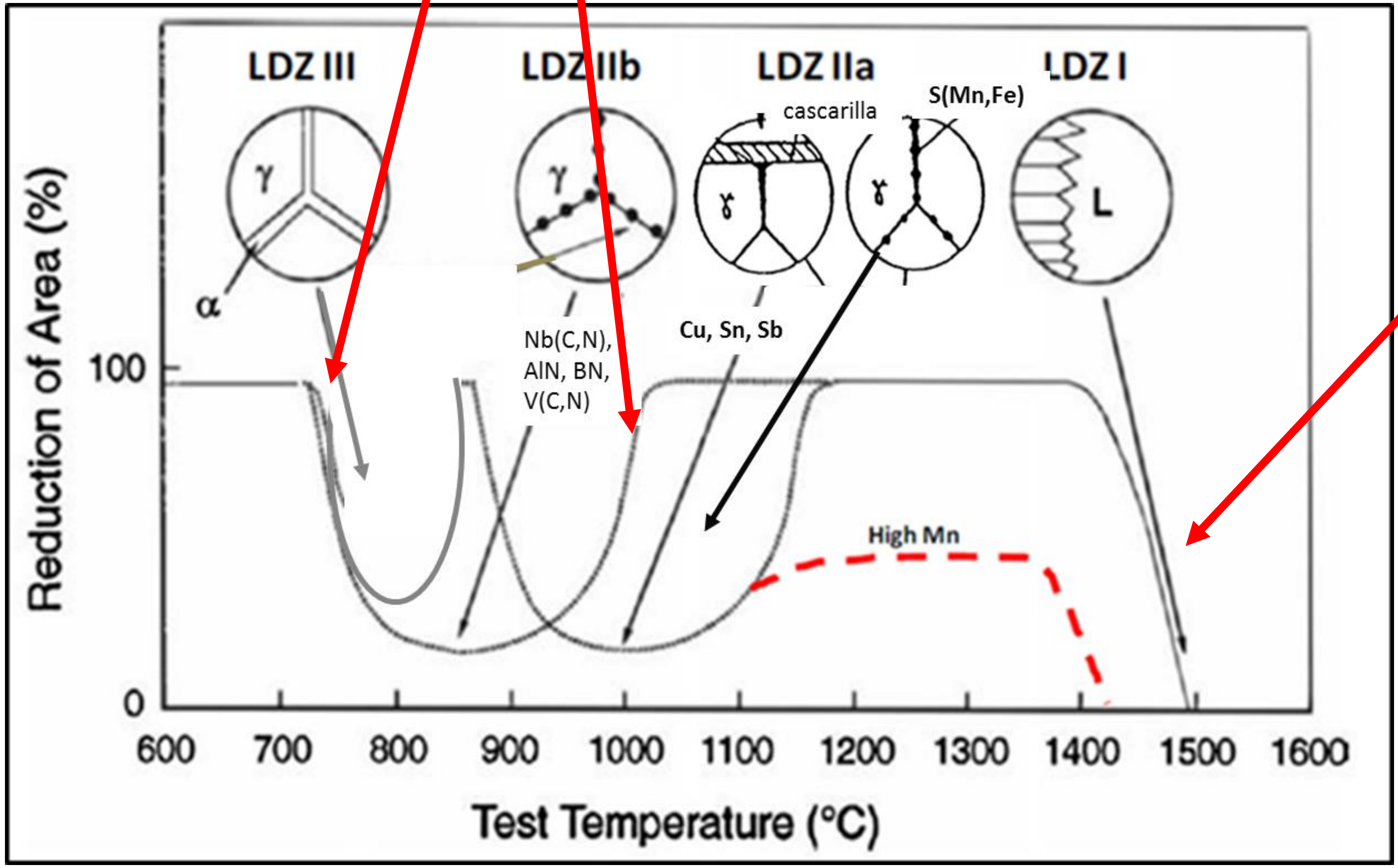
1. Introduction

Ductility troughs related to surface cracking of present study

High temperature ductility troughs during solidification and cooling of the CC billet



The internal segregation cracking is related to the low ductility range during solidification

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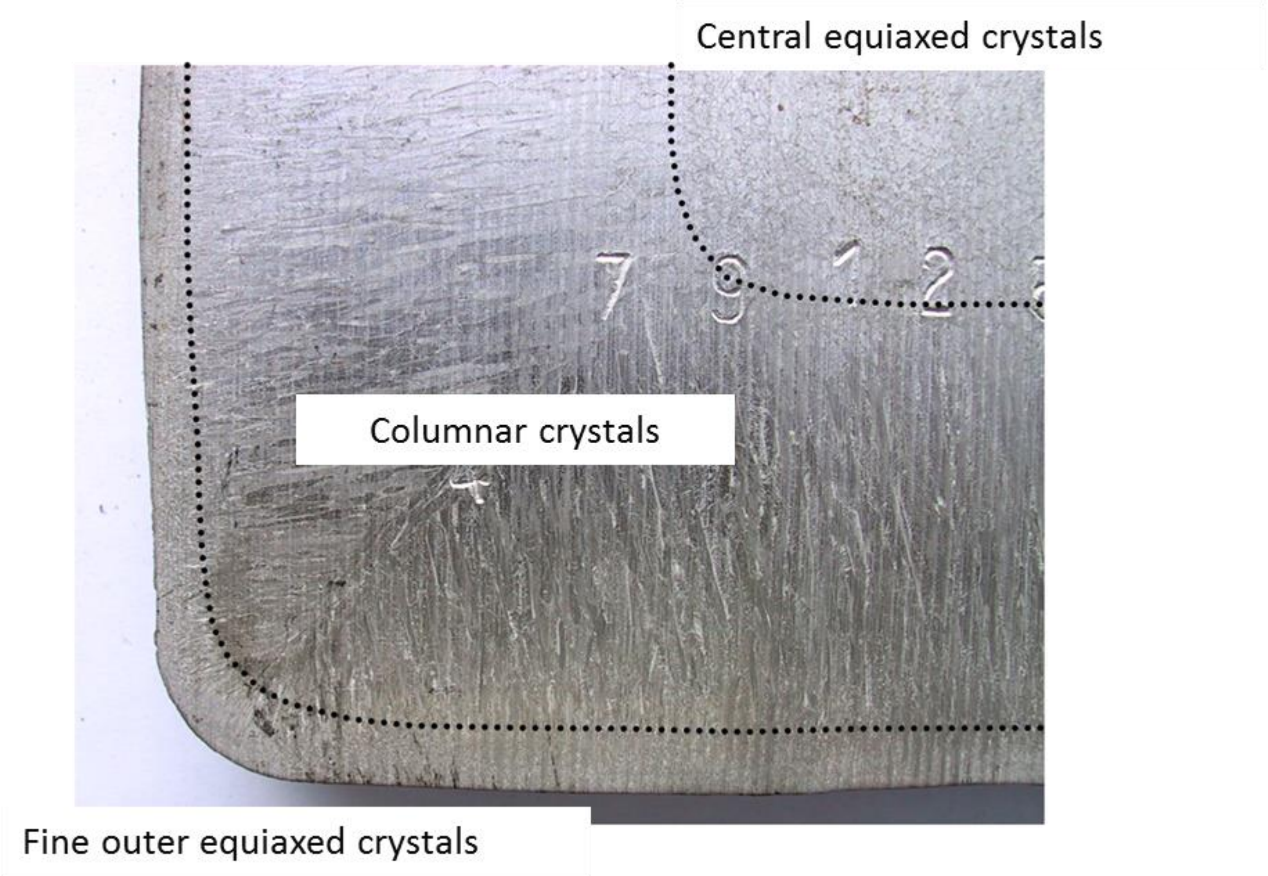
SEGREGATION CRACKING FORMATION MECHANISM

2. Segregation cracking formation mechanism

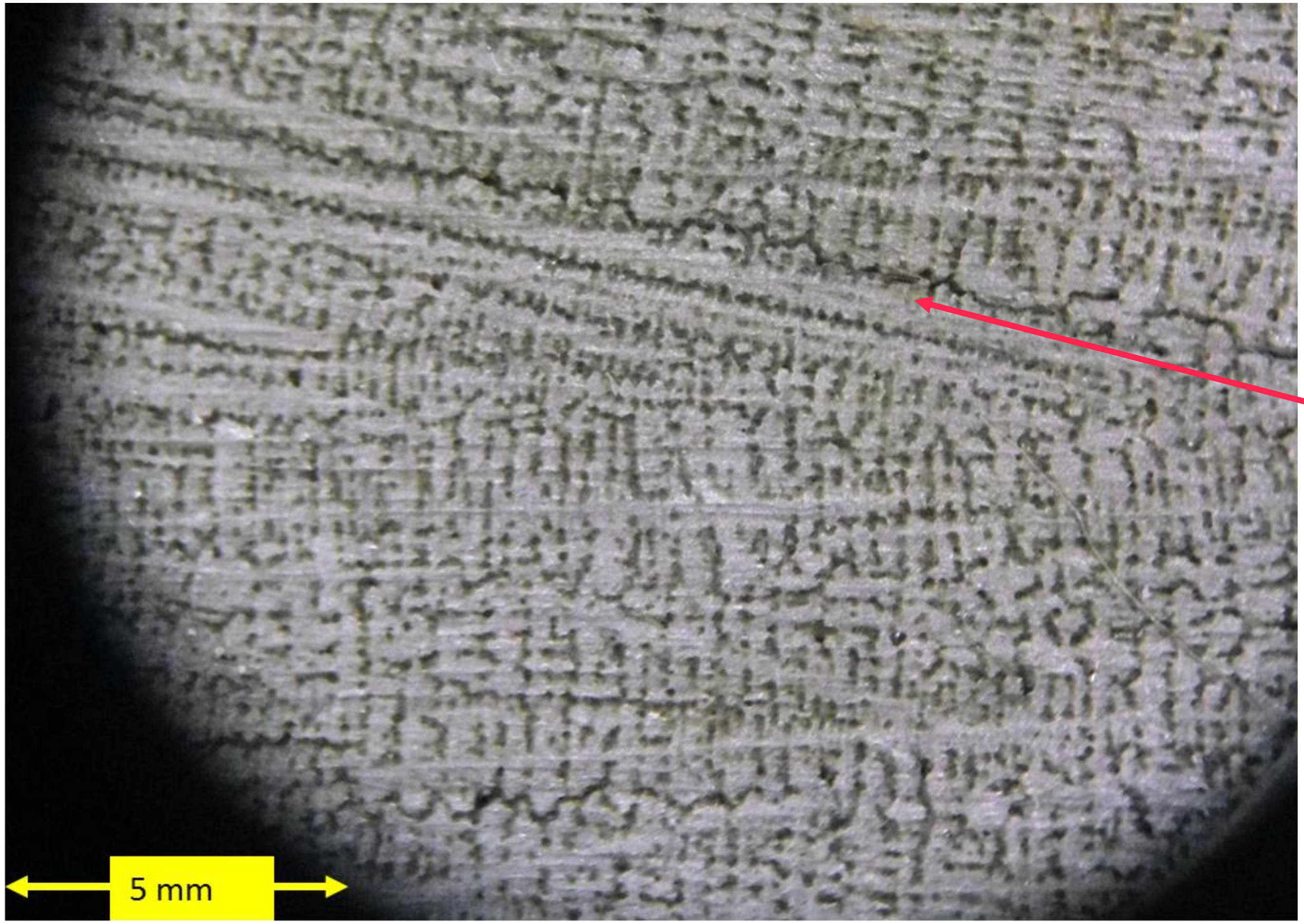
- Billet internal solidification macrostructure



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.

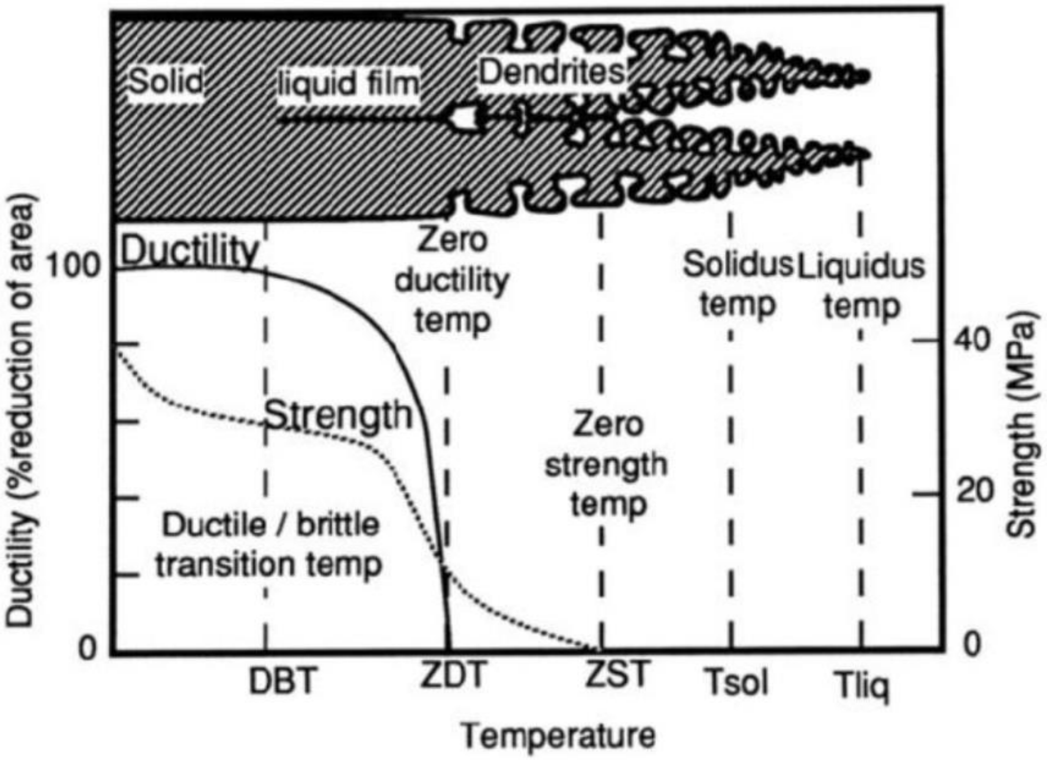


Hot acid etching of a billet transversal sample reveal the presence of segregation cracks between dendrites.

2. Segregation cracking formation mechanism

- **Which is the effect of a stress on the solidification dendrites?**
  - Depends upon the solid fraction (**F_S**):
    I. For low **F_S** the free movement of liquid is able to fill stress created cracks.
    II. For **F_S** > 0.6 the material have some strength, but no deformation at all: Zero Strength Temperature (ZST).
    III. For **F_S** > 0.9 Some deformation is produced. Ductile fracture. Zero Ductility Temperature (ZDT).
    IV. Along the temperature interval ZST-DBT the solidifying shell can be easily fracture, and the corresponding crack is filled with residual interdendritic.

- **Some chemical elements have a high influence on the magnitude of the ZST-DBT temperature interval.**

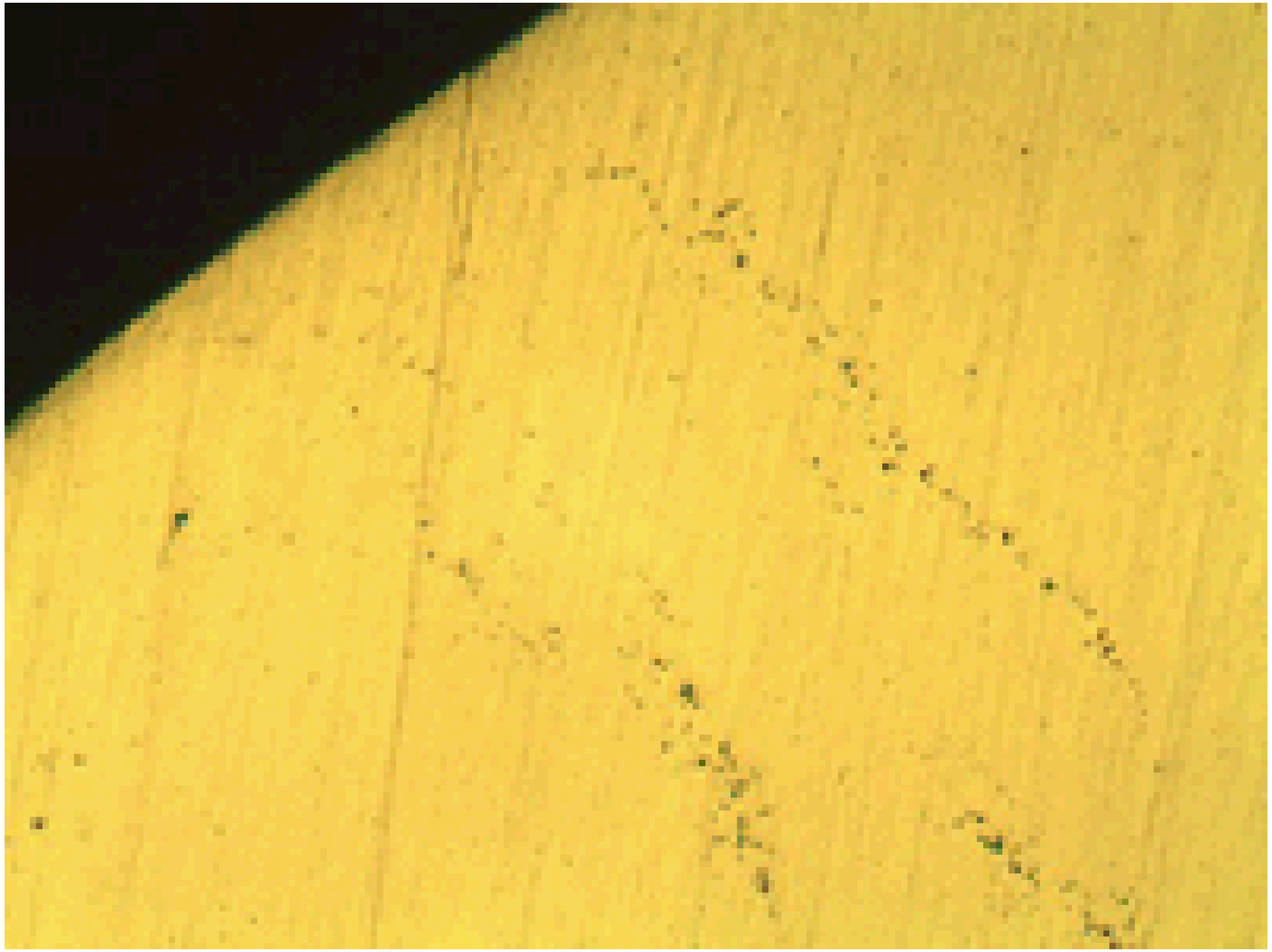


ZST: Zero Strength Temperature
ZDT: Zero Ductility Temperature
DBT: Ductile Brittle Temperature transition

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

2. Segregation cracking formation mechanism

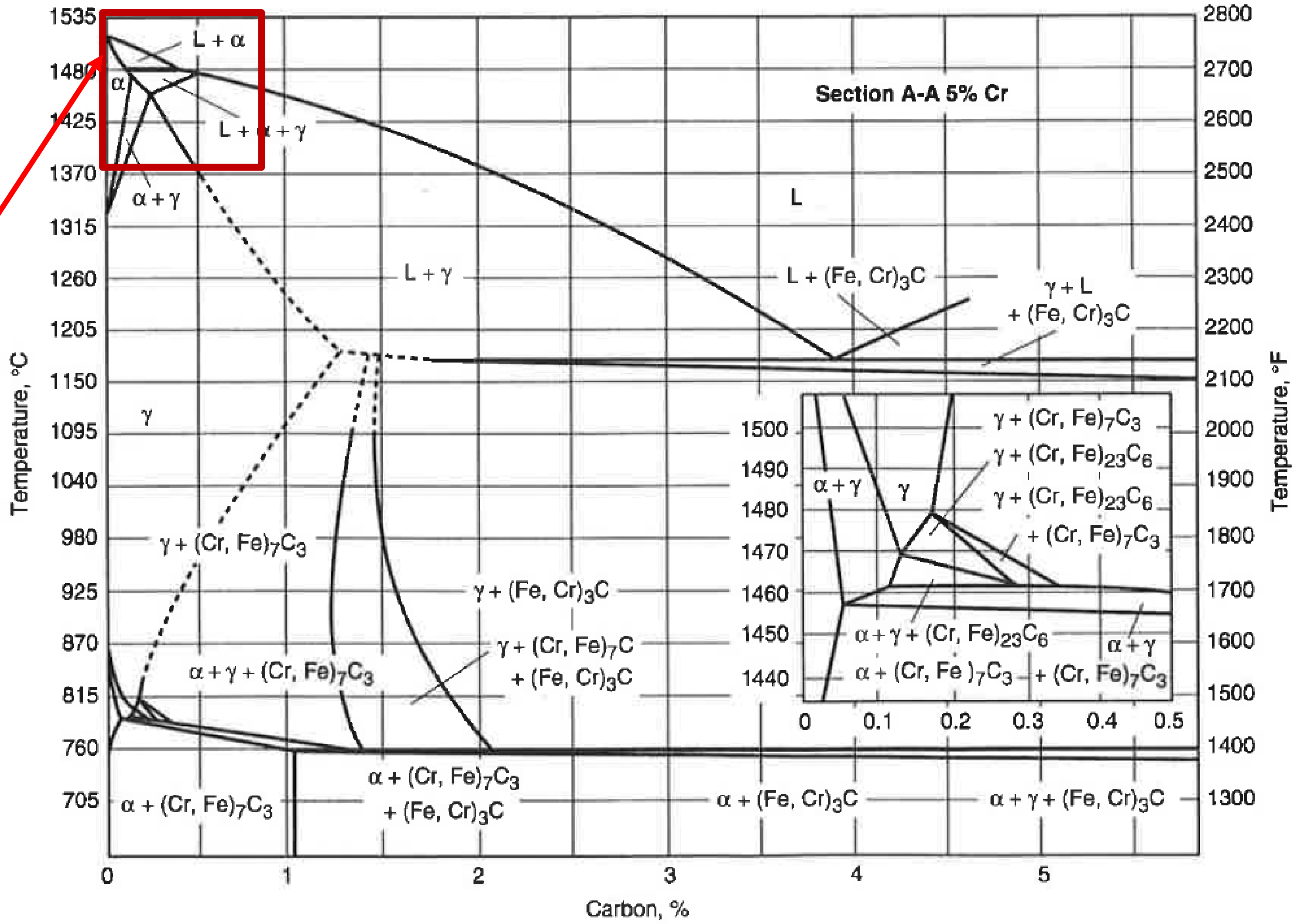
Example of the presence of segregation cracks on a rolled bar. The segregated cracks appears as a zone with a high presence of elements which segregate during solidification, mainly MnS.



2. Segregation cracking formation mechanism

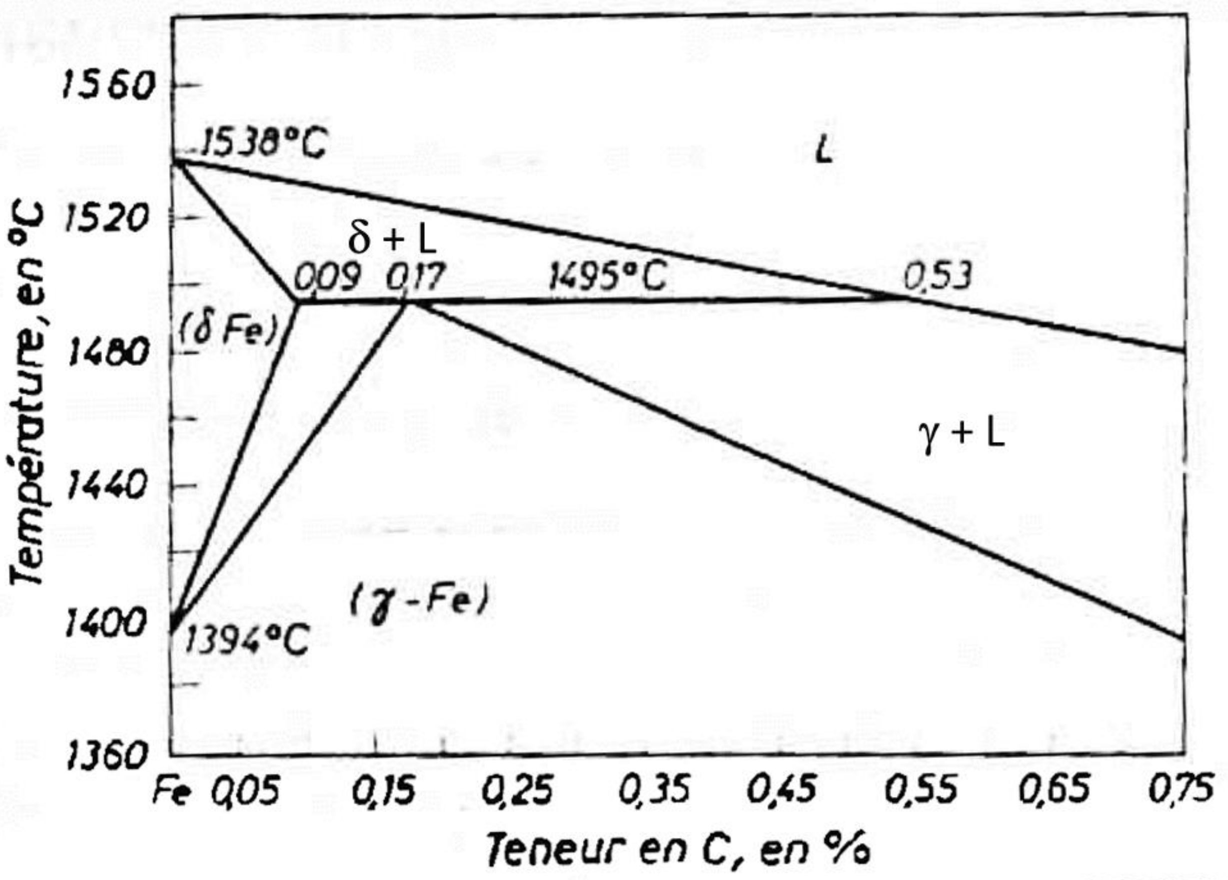
- **Fe-C Diagram**

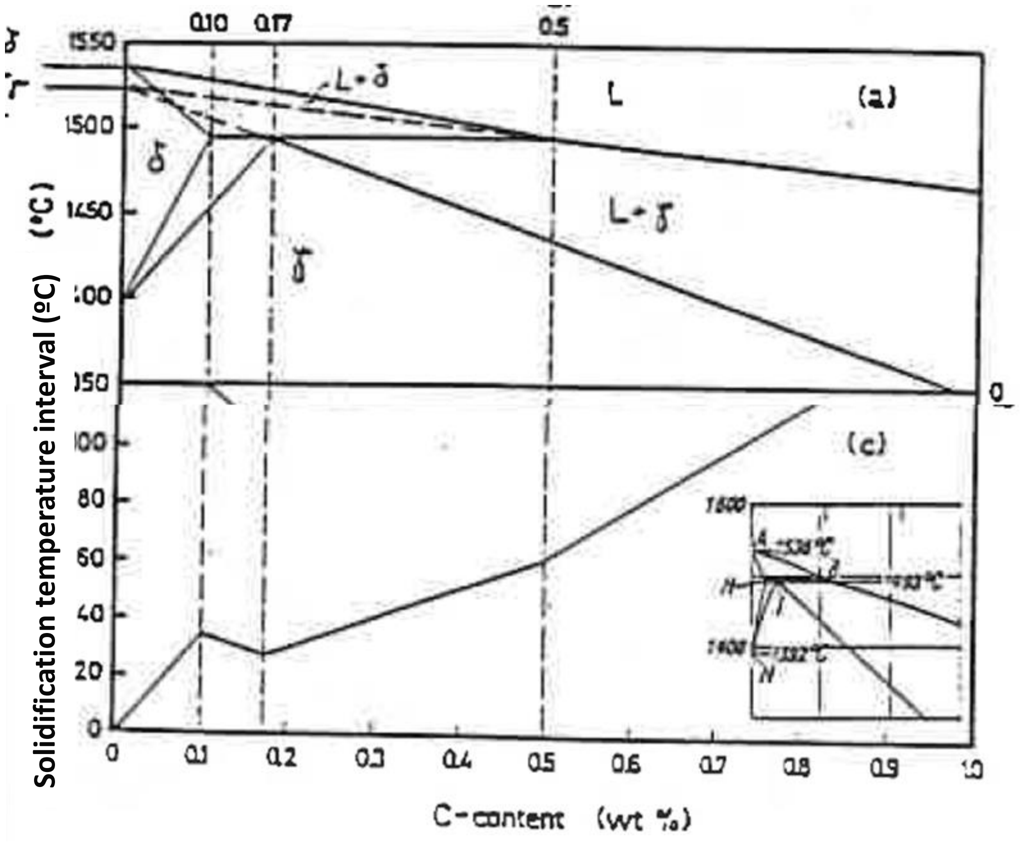
Segregation cracks are related with this area of the Fe-C equilibrium phase diagram where solidification of steel grades is placed



2. Segregation cracking formation mechanism

- **Fe-C equilibrium phase diagram**



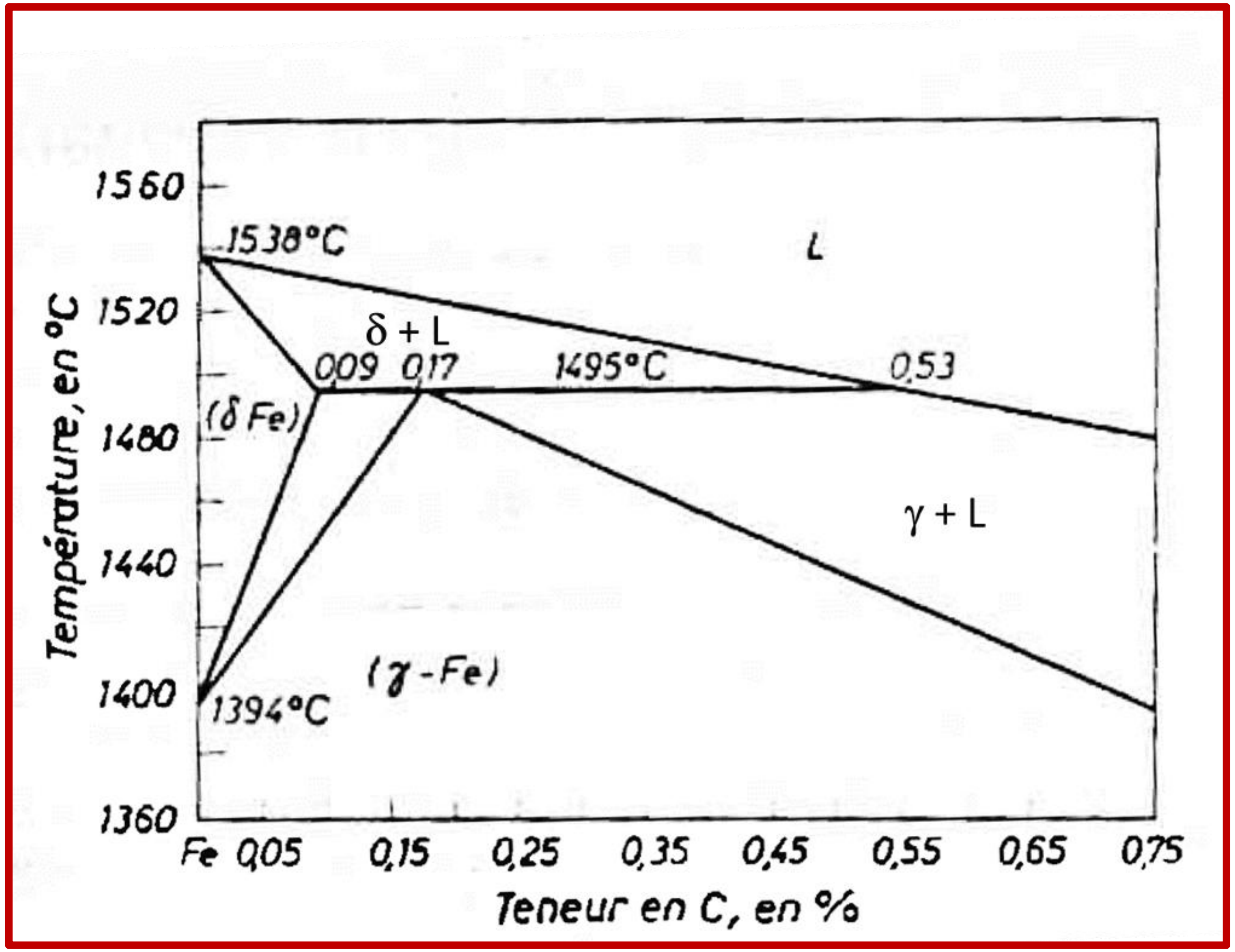


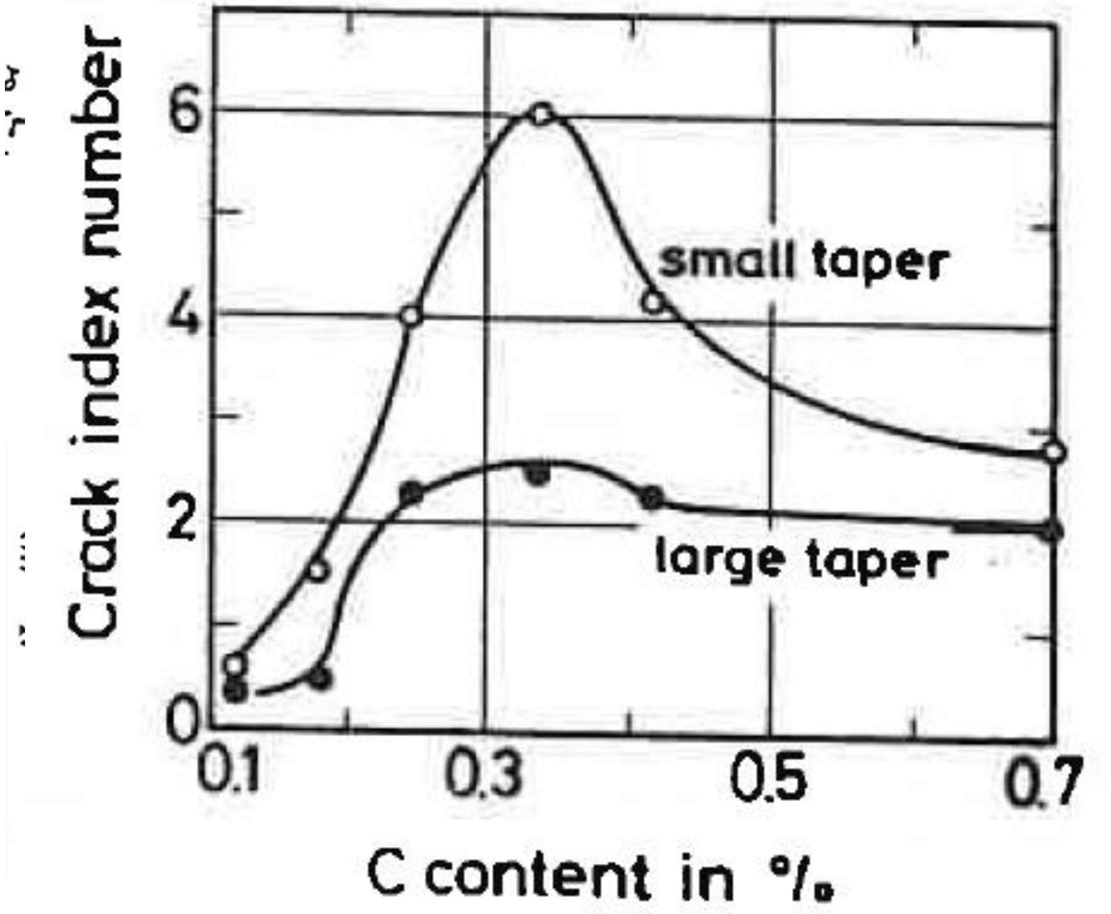
M. Wolf. 1st ECCC Florence, 1991, V. 2, 489-499

Segregation cracks depend on solidification temperature interval, which increases with carbon content. Furthermore, C controls the primary solidification phase, and for this same reason, also the segregation of other chemical elements like S and P.

2. Segregation cracking formation mechanism

- **Fe-C equilibrium phase diagram**

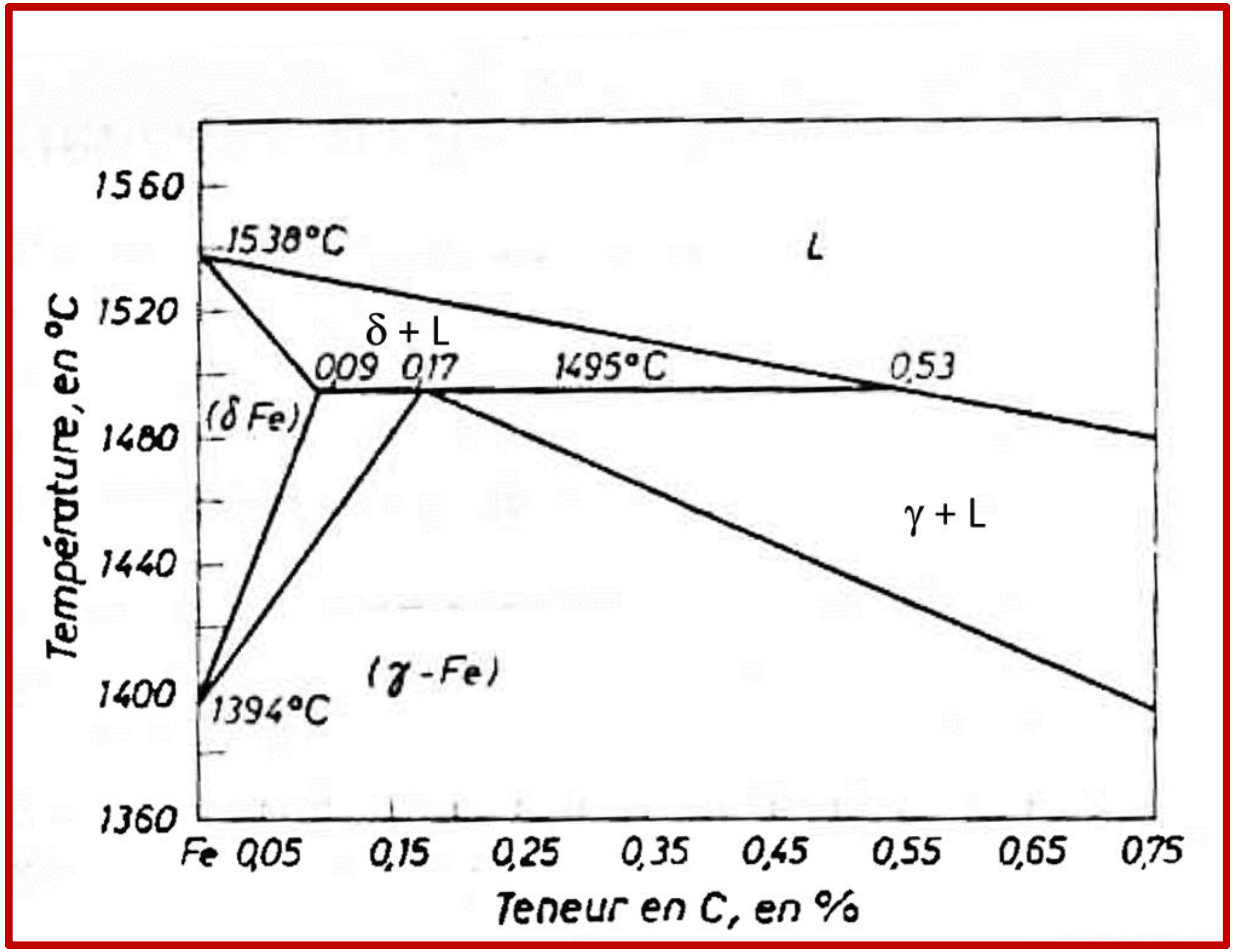




C influence on the formation of segregated cracks.
R. Jauch et al. Met Plant Technol. 1, N. 2, 24-33, 1978

2. Segregation cracking formation mechanism

- **Effect of highly segregated chemical elements on solidification microstructure:**



Partition coefficient during primary phase solidification, K, is defined by:

$$K_\delta = \frac{C_0}{C_L} = 0.09/0.53 = 0.17$$

Where C_0 and C_L are the solid and liquid compositions at equilibrium.

Values of the partition coefficient for sulfur are:

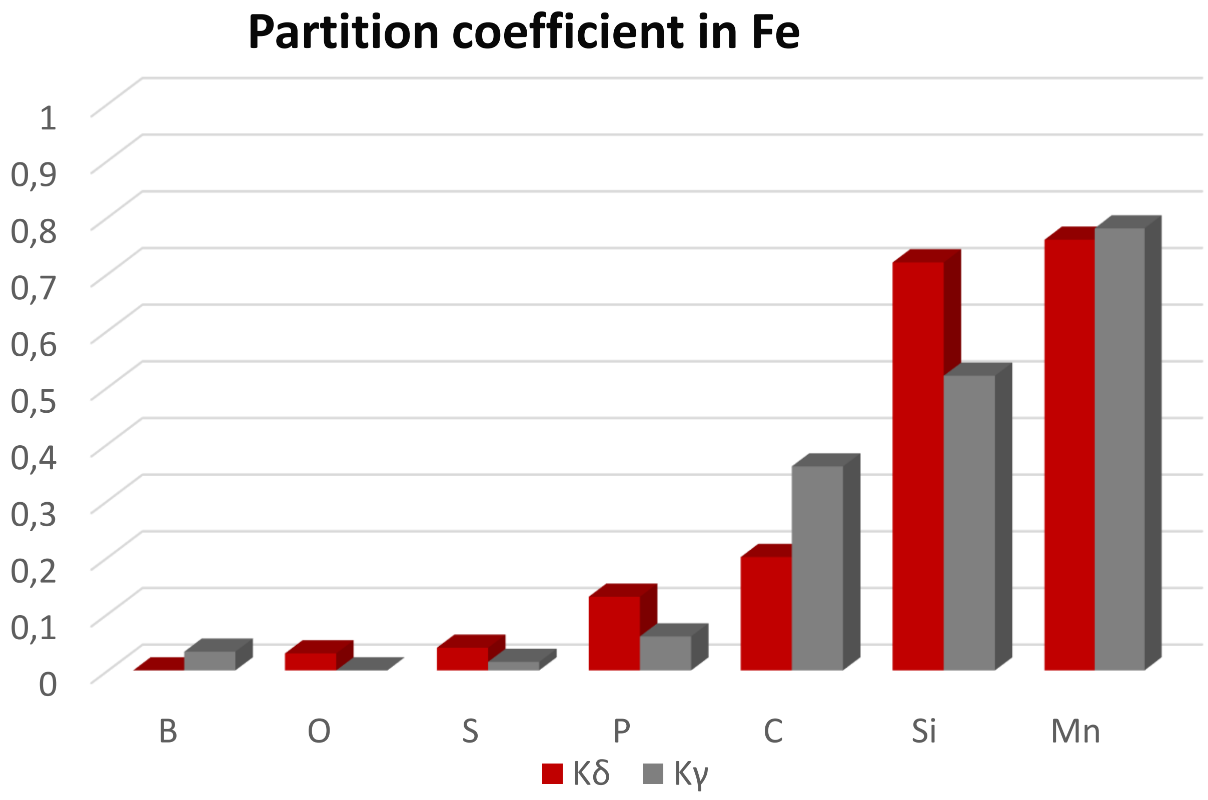
$$K_\delta = \frac{C_0}{C_L} = 0.05 \qquad K_\gamma = \frac{C_0}{C_L} = 0.015$$

So a small value of the partition coefficient for S indicates that the solid dissolve little S and the majority of this element accumulate in solid liquid interphase front. This means that if the primary phase is austenite, and 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%

2. Segregation cracking formation mechanism

- **Effect of highly segregated chemical elements on solidification microstructure:**

Each element has its own K coefficients, which depends on the solid phase where the element solidifies.



The partition coefficient of each chemical element depends on the primary solidification 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.

The highest segregated chemical elements are B, O, S and P. On killed steels it is almost no free oxygen in the liquid steel. P could produce segregation problems, However for the usual content of this elements on special steels the experience shows that this element is not enhancing segregation cracking. The more problematic chemical elements are B and S, and the study will concentrate on both of them.

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2. Segregation cracking formation mechanism

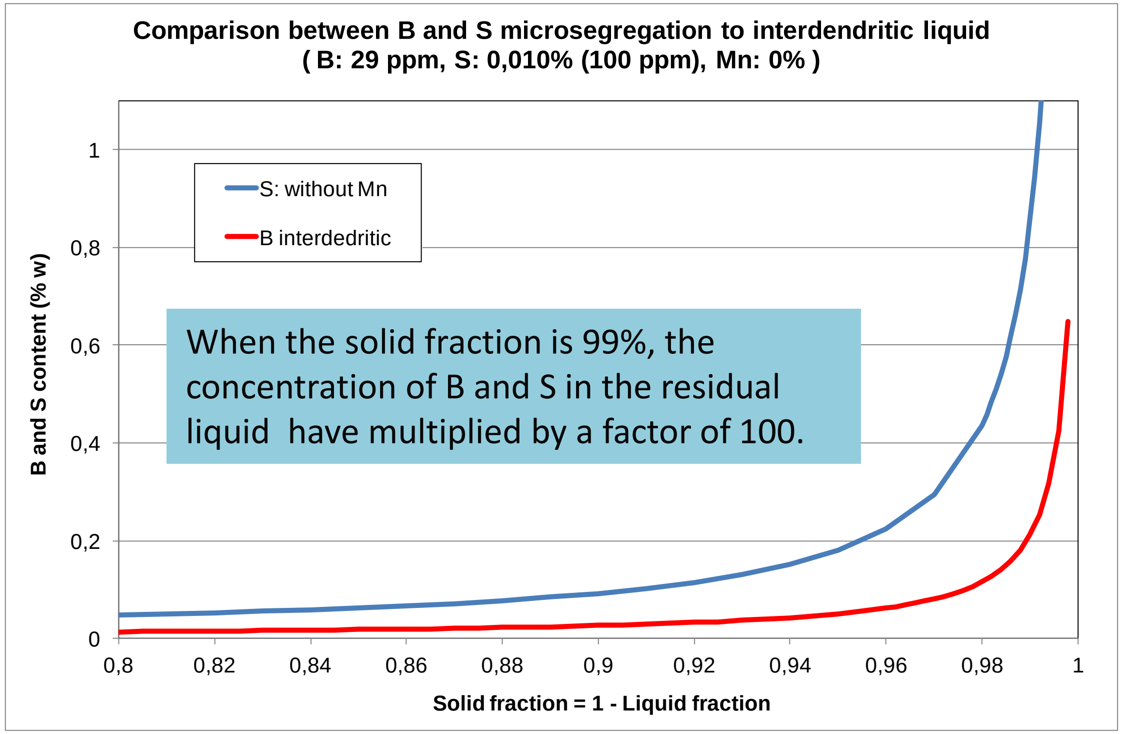
- **Effect of highly segregated chemical elements on solidification microstructure:**

What happens when the interphase liquid enriches with segregated elements?
The concentration of the interphase liquid can be approximately calculated by the Sheill-Gulliver equation:

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

In the case of B and S: the segregated interdendritic liquid with a high content of S or B have a low solidification temperature.

B and S widen the ZDT-ZST, therefore, they make the steel more segregation cracking susceptible during solidification.



2. Segregation cracking formation mechanism2

- **Effect of highly segregated chemical elements on solidification microstructure:**

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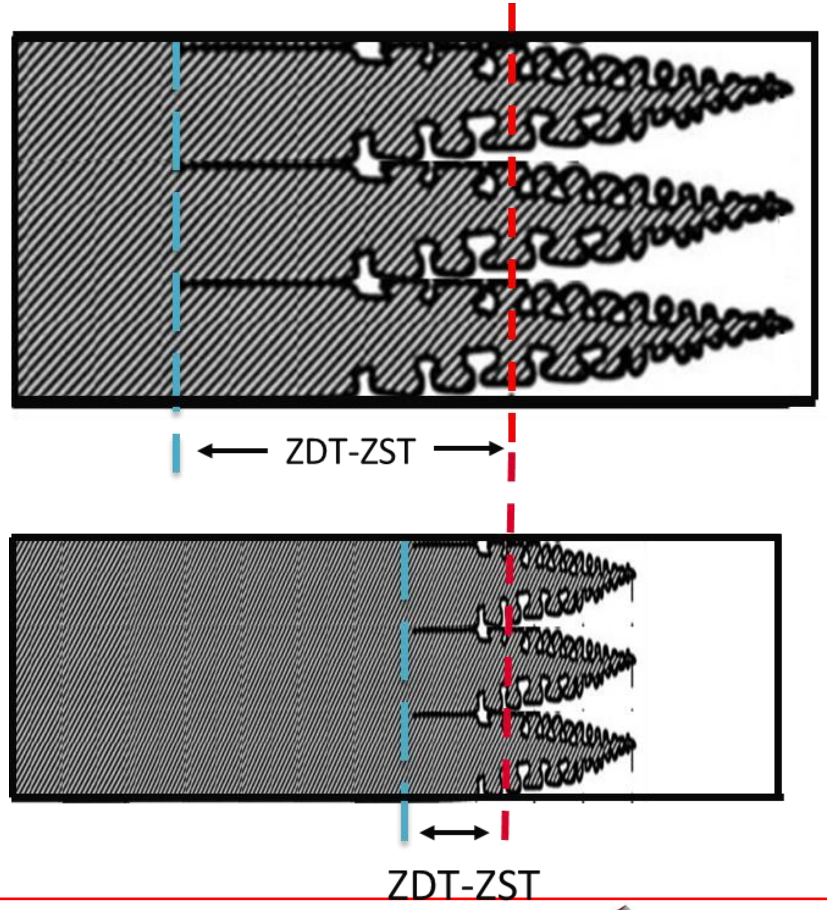

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3. Influence of composition on segregation cracking: Sulphur.

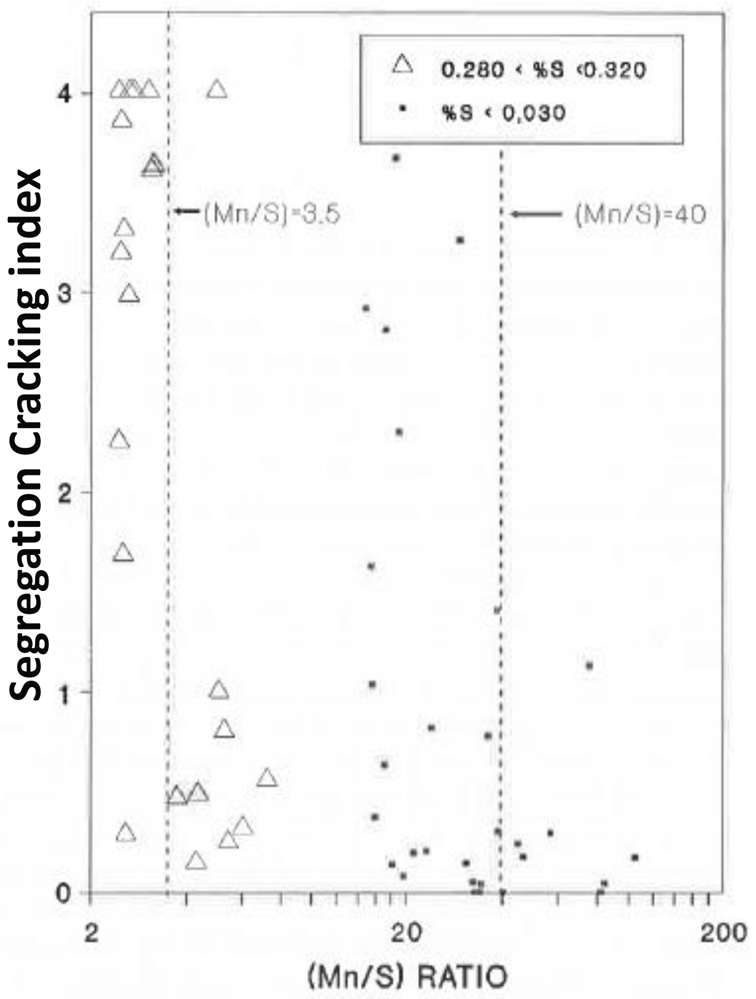
3. Influence of composition on segregation cracking: Sulfur

- Many years ago at the very beginning of the CC process, improvements on CC billets were obtained decreasing the S content.
- However, the necessity for better machining of the rolled bars has raised the S content requirements of customers.
- The Mn/S ratio decrease the problems related to S segregation: how and why?

The figure shows two Mn/S ratios which are the borders between good and bad results. 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

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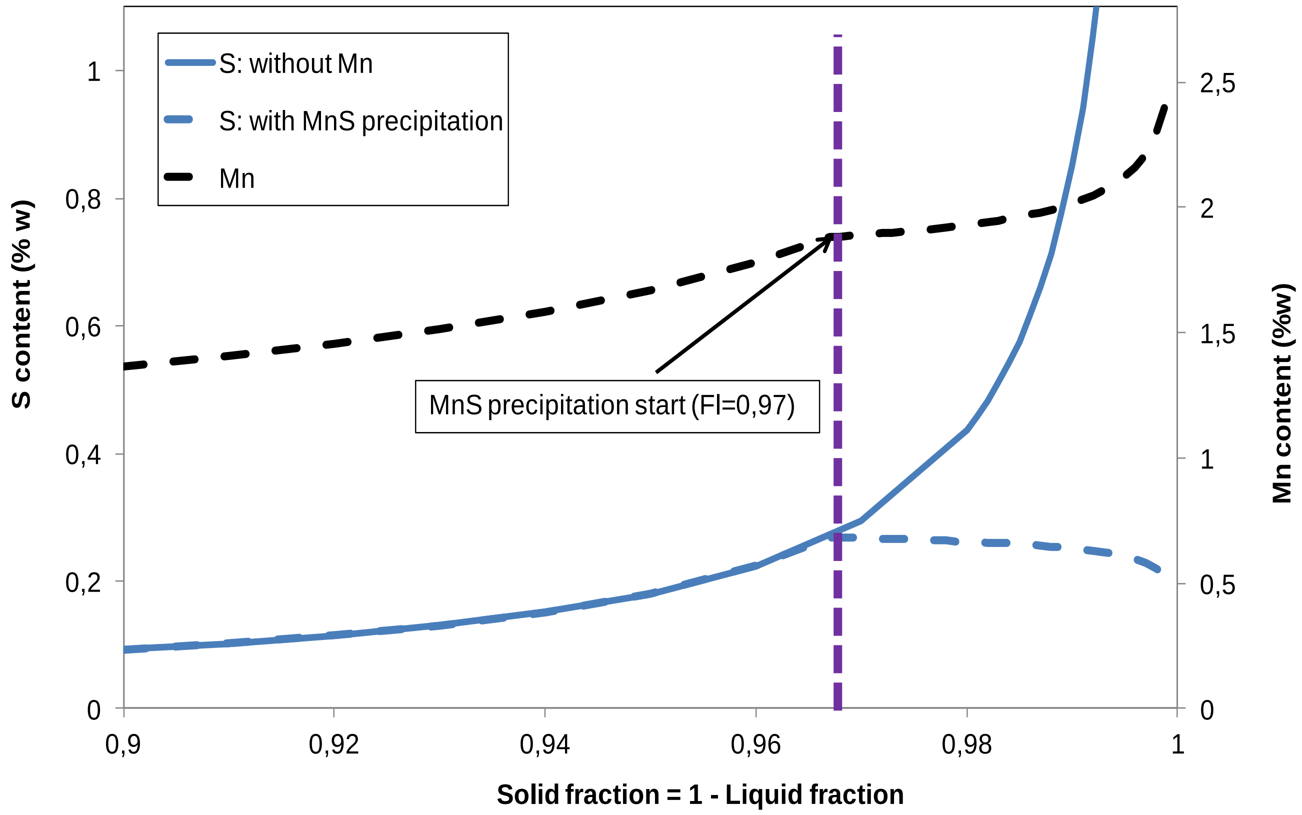
3. Influence of composition on segregation cracking: Sulfur

- **Effect of Mn addition to a steel grade with S**
- **Case 1:** S=0,010%, Mn=0,70%

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



- MnS precipitation begins for Fs = 0.97
- Once MnS precipitation starts, sulfur is consumed as solidification progresses and more MnS is precipitated.
- **Sulfur is consumed in the residual liquid** and no melting liquid is produced.

Low tendency to segregation cracking

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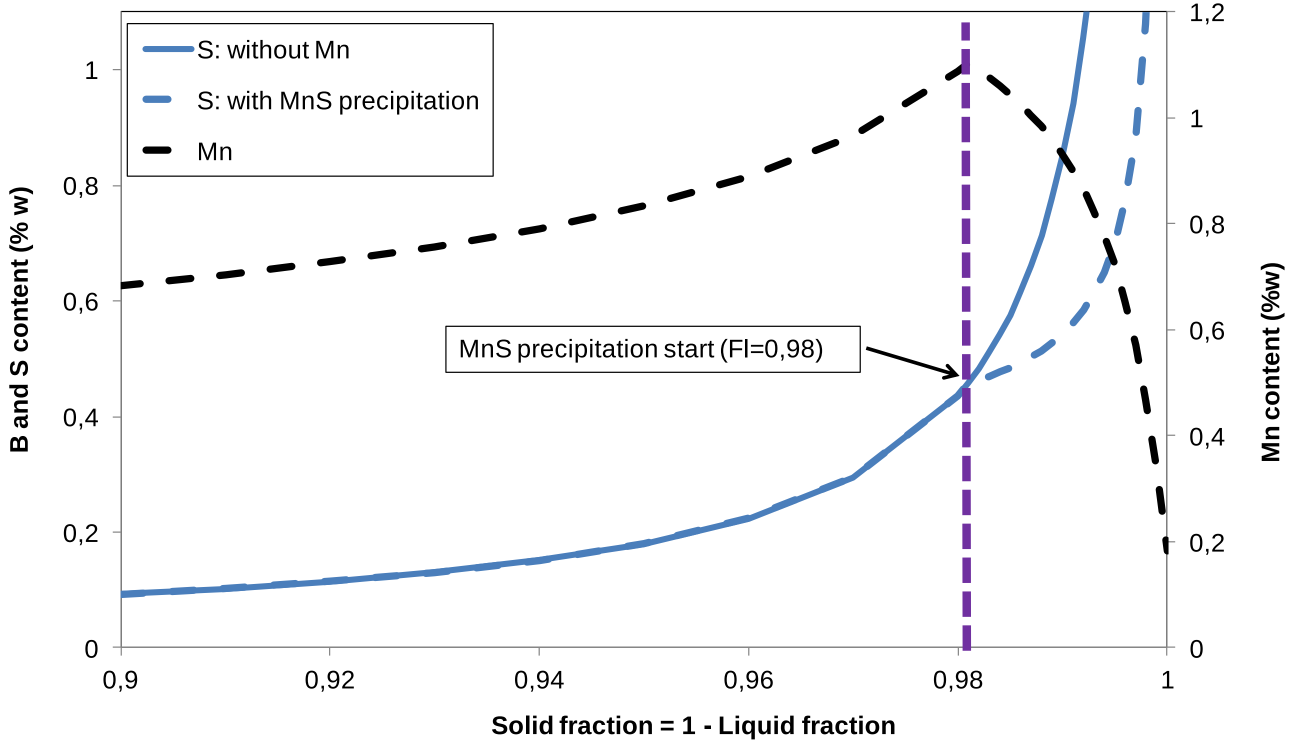
3. Influence of composition on segregation cracking: Sulfur

- **Effect of Mn addition to a steel grade with S**

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

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

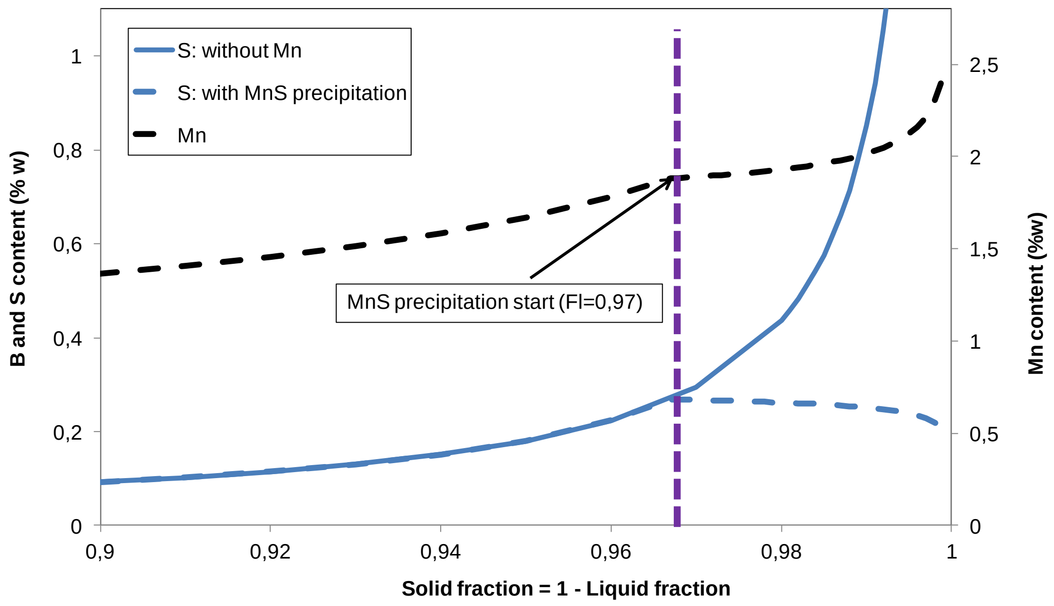


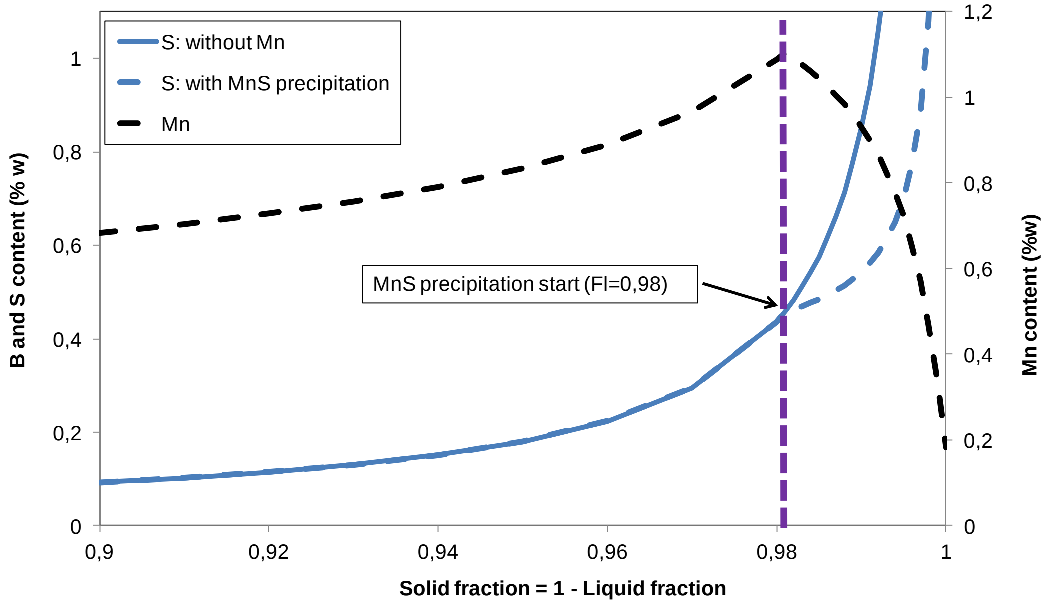
- MnS precipitation begins for Fs: 0,98.
- The **manganese content in the residual liquid decreases** as solidification and precipitation is progress.
- Low melting interdendritic liquid is produced which solidifies around 1000 ºC with the precipitation of FeS. .

High tendency to internal cracking

3. Influence of composition on segregation cracking: Sulfur

- **Effect of Mn addition to a steel grade with S**





Low internal cracking tendency

High internal cracking tendency

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

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

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

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3. Influence of composition on segregation cracking: Sulfur

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

By means of theoretical calculations and experimental data, this equation is obtained for the Mn/S critical ratio which differentiates a progressive intendendritic liquid enrichment of S and the case in which S consumes.

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

Depends only on the S content of the Steel.

IF $\frac{Mn}{S} > \left(\frac{Mn}{S}\right)_C$ LOW CRACKING TENDENCY

IF $\frac{Mn}{S} < \left(\frac{Mn}{S}\right)_C$ HIGH CRACKING TENDENCY

- **MSC coefficient**

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

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

MSC>1 LOW CRACKING TENDENCY

MSC<1 HIGH CRACKING TENDENCY

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3. Influence of composition on segregation cracking: Sulphur.

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

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

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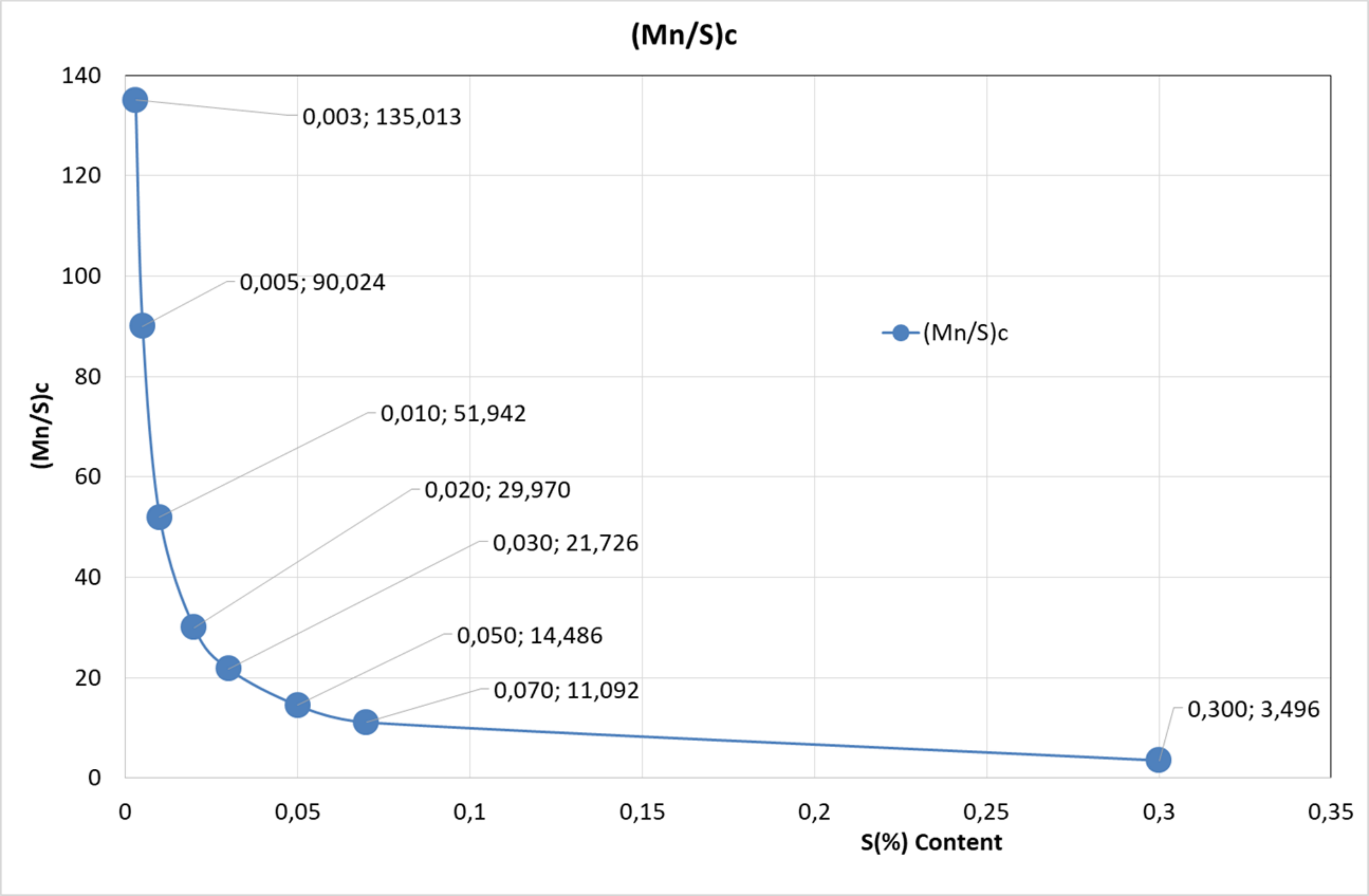
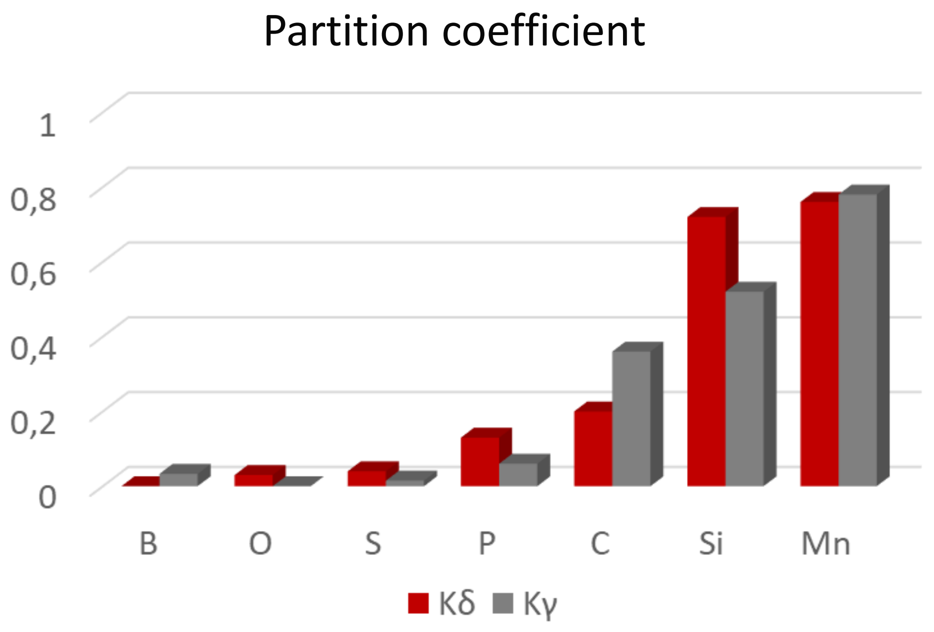


INFLUENCE OF COMPOSITION ON SEGREGATION CRACKING: BORON

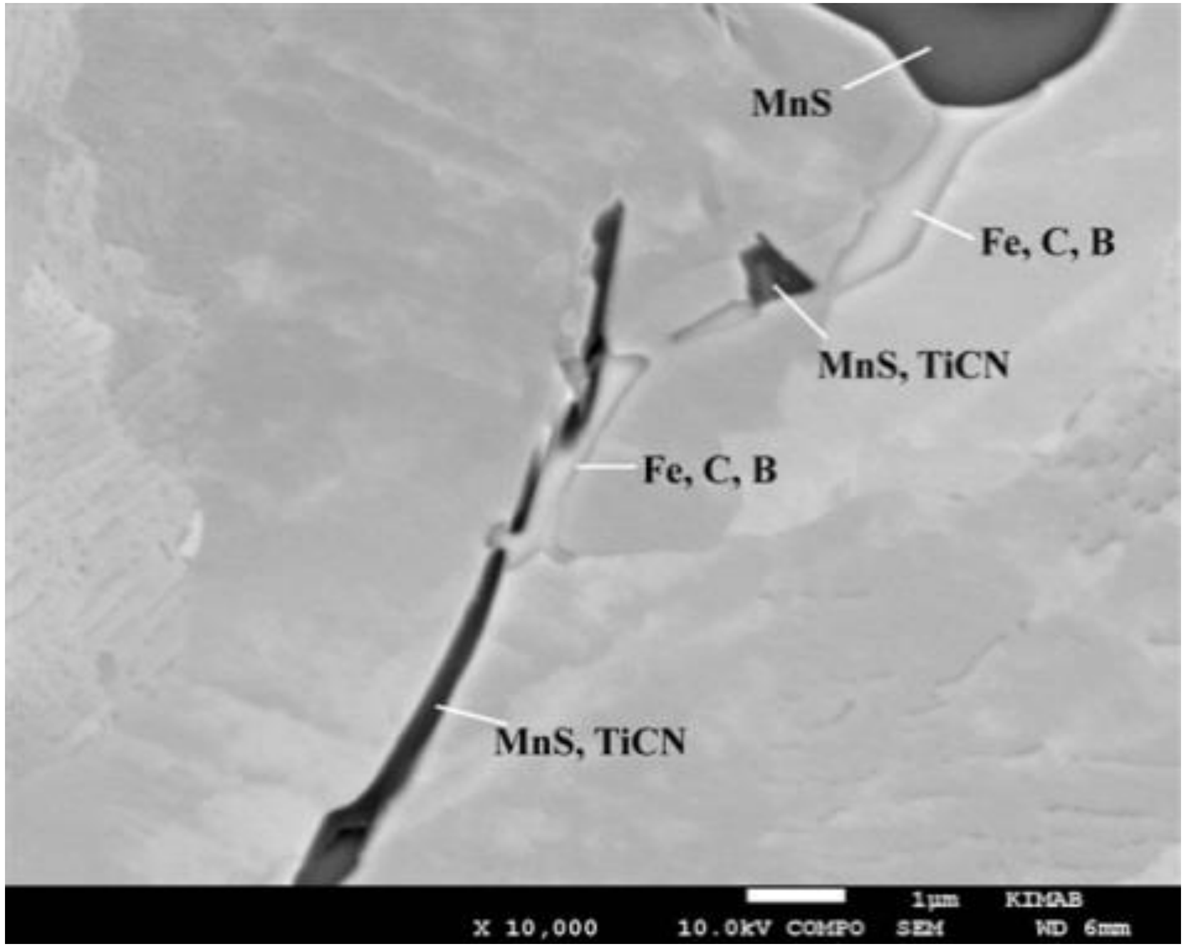
3. Influence of composition on segregation cracking: Boron

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

$(K_{\gamma})^{B} = 0{,}003$



Half-way crack in a 30MnCrB5E steel grade: MSC>1

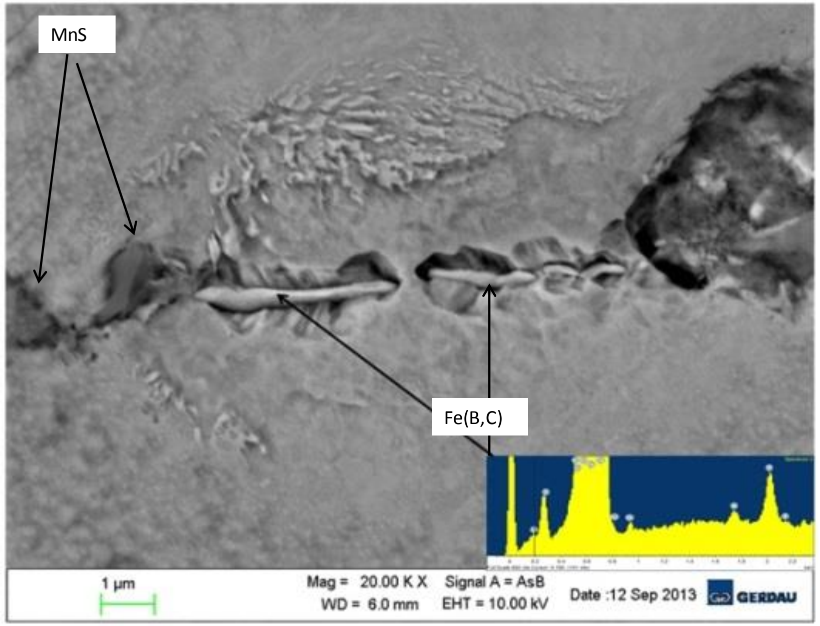


Alvarez de Toledo et al.: (PMAP). RFSR-CT-2012-00008

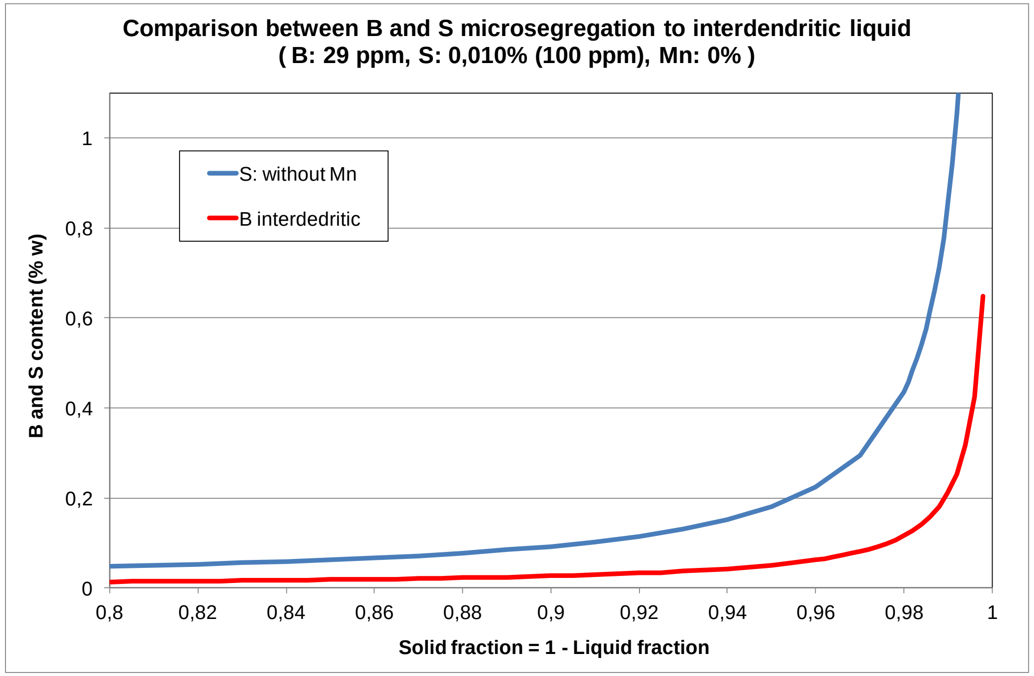
3. Influence of composition on segregation cracking: Boron

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

K_B=0,003



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.

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INTERNAL SEGREGATION CRACKING CLASSIFICATION

4. Internal segregation cracking classification

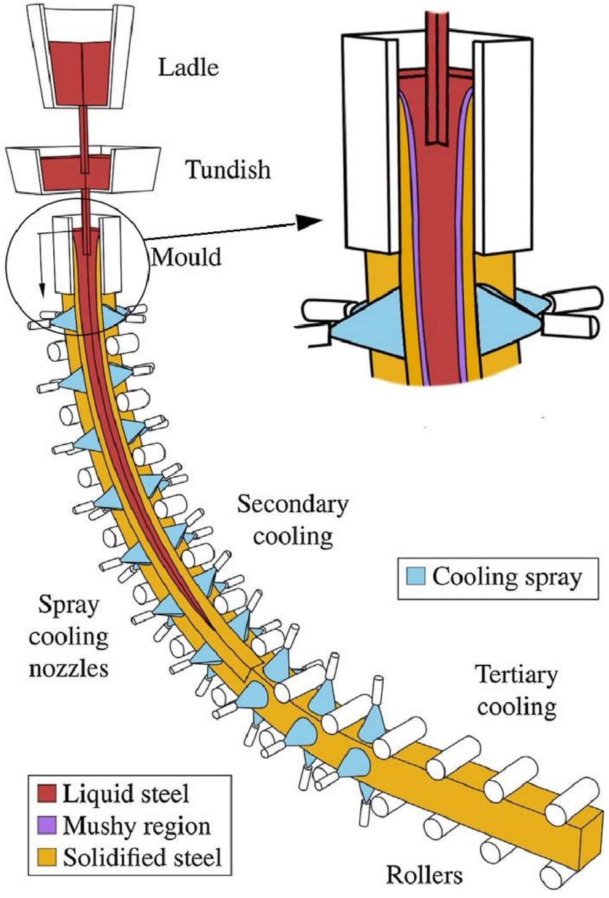
Internal deffects

Segregation cracks

- Susceptible chemical compositions
- Stresses at the solid shell

The parameters which influence the appearance of segregation cracks are both the presence of a stress at the solidification interphase, and a chemical composition with segregation crack tendency.

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

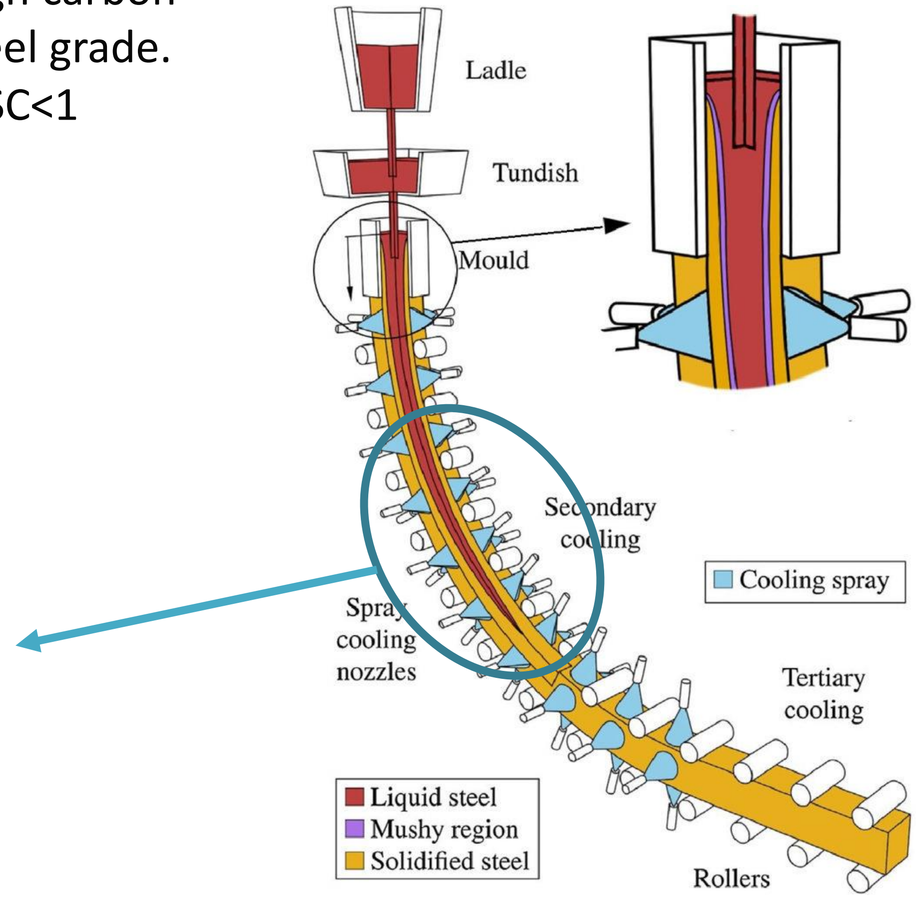


Credits: *Klimes and Stetina*

4. Internal segregation cracking classification

1. Half-way cracks.

High carbon
Steel grade.
MSC<1



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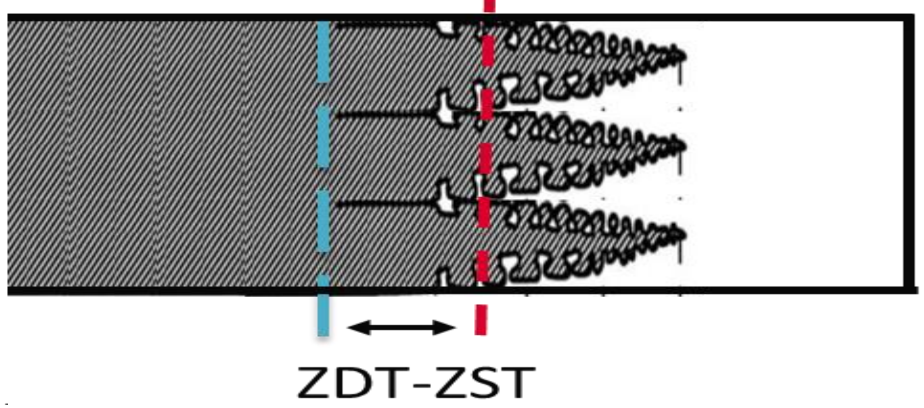
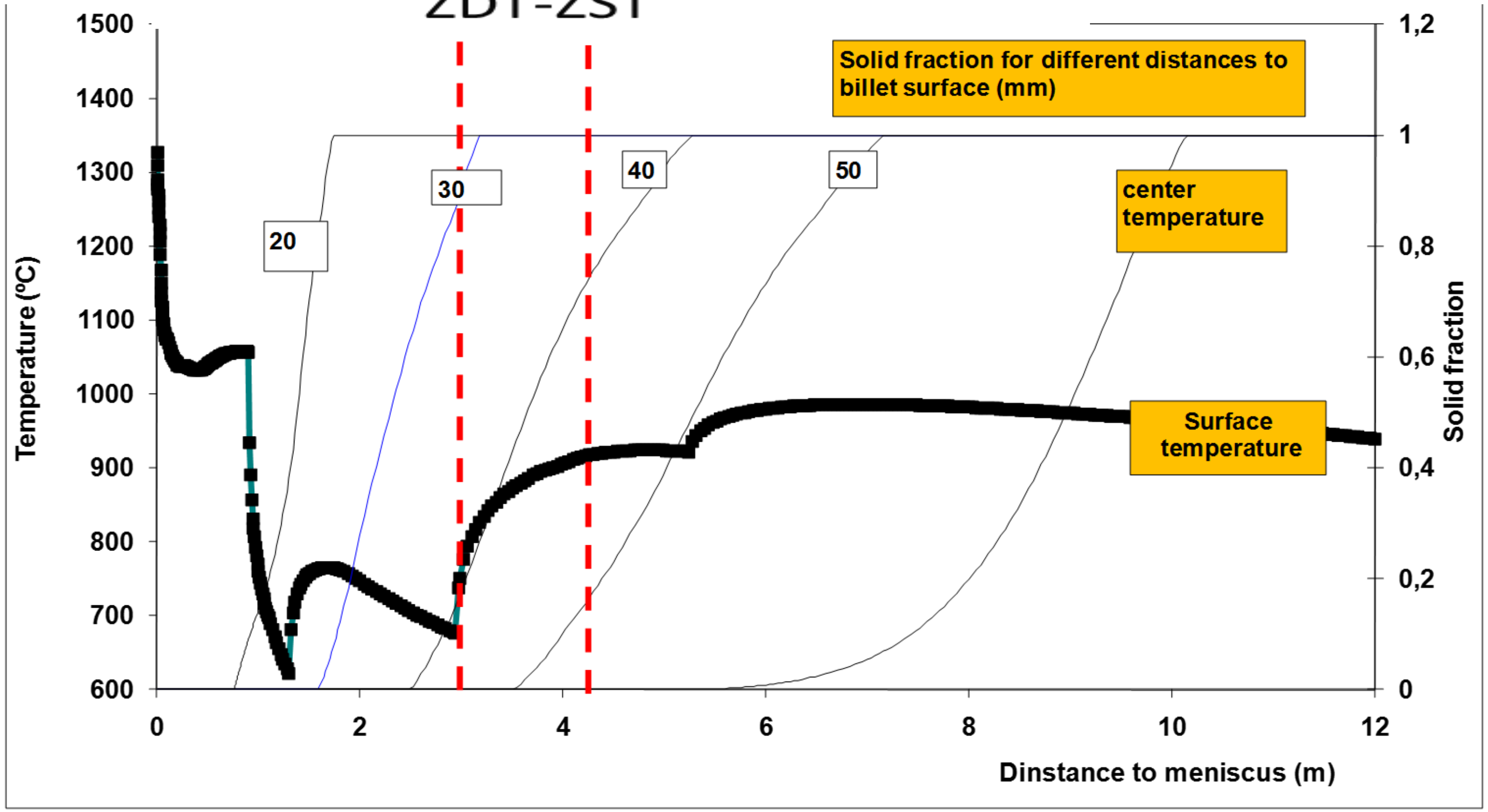


DISTEMP program calculation of the temperature and solid fraction for different distances to the billet Surface. The water cooling intensity at secondary cooling zone Zone II is too high, and at the transition between Zones II and III a big surface reheating takes place, leading to half-way cracking.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



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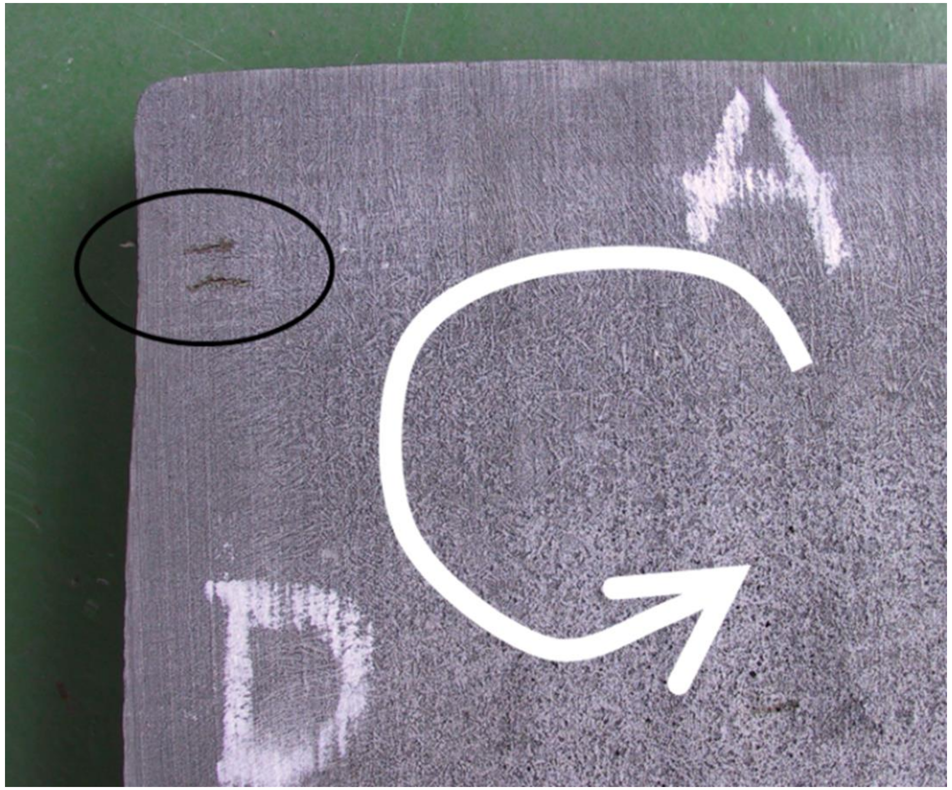
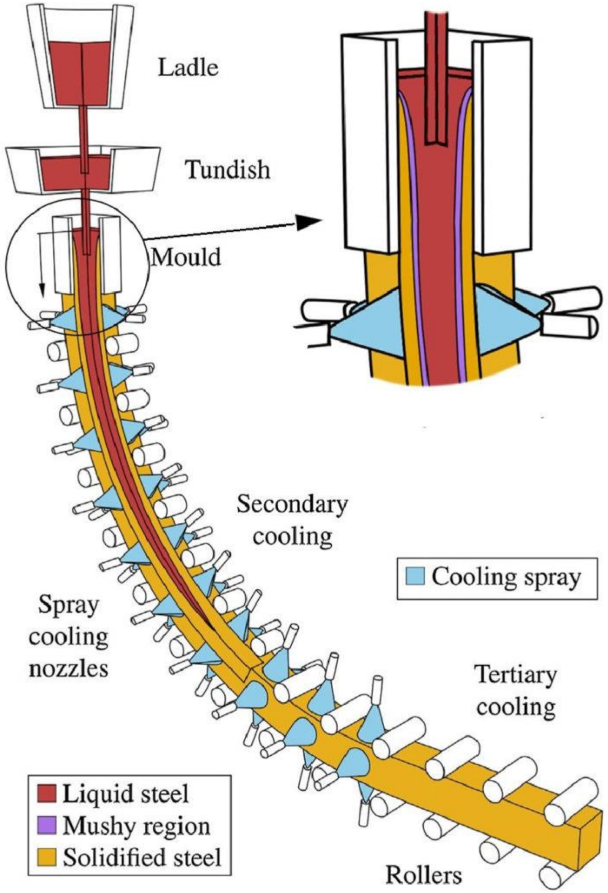
4. Internal segregation cracking classification

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. DISTEMP solidification modeling shows that those depths corresponds to the lower part of the mold or just after mold exit.



The importance of this off-corner cracking is that these are internal cracks and they are not detected in the common surface control of rolled bars. However, these cracks produce defects when the material is hot or cold forged at the customer site.



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4. Internal segregation cracking classification

2. Off-Corner cracks

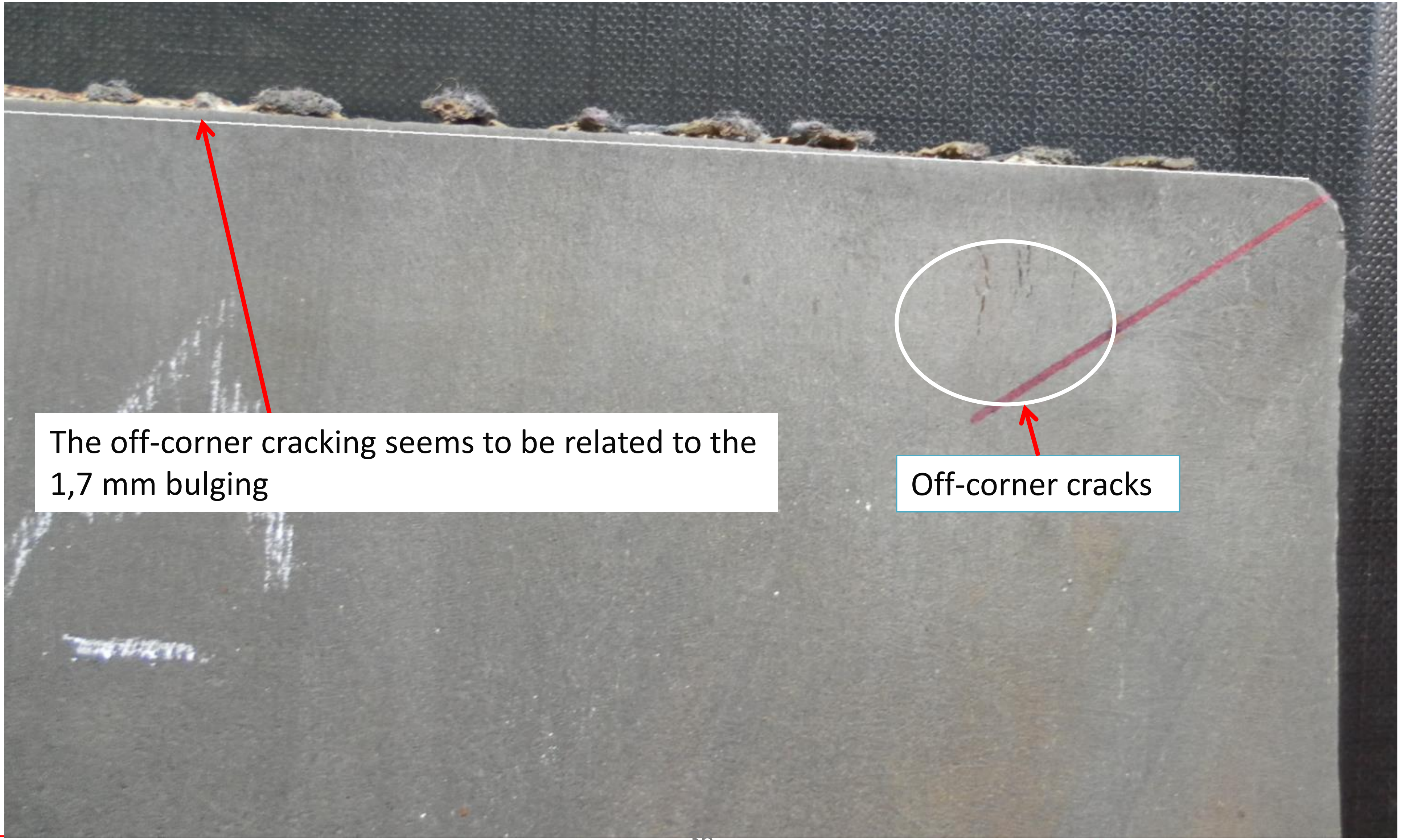
Off-corner cracks produce a lack of homogeneity in the product surface during the end of machining process at customer.

Segregation induced cracking during the hot/cold forge, or in the induction quenching.

4. Internal segregation cracking classification

2. Off-Corner cracks

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



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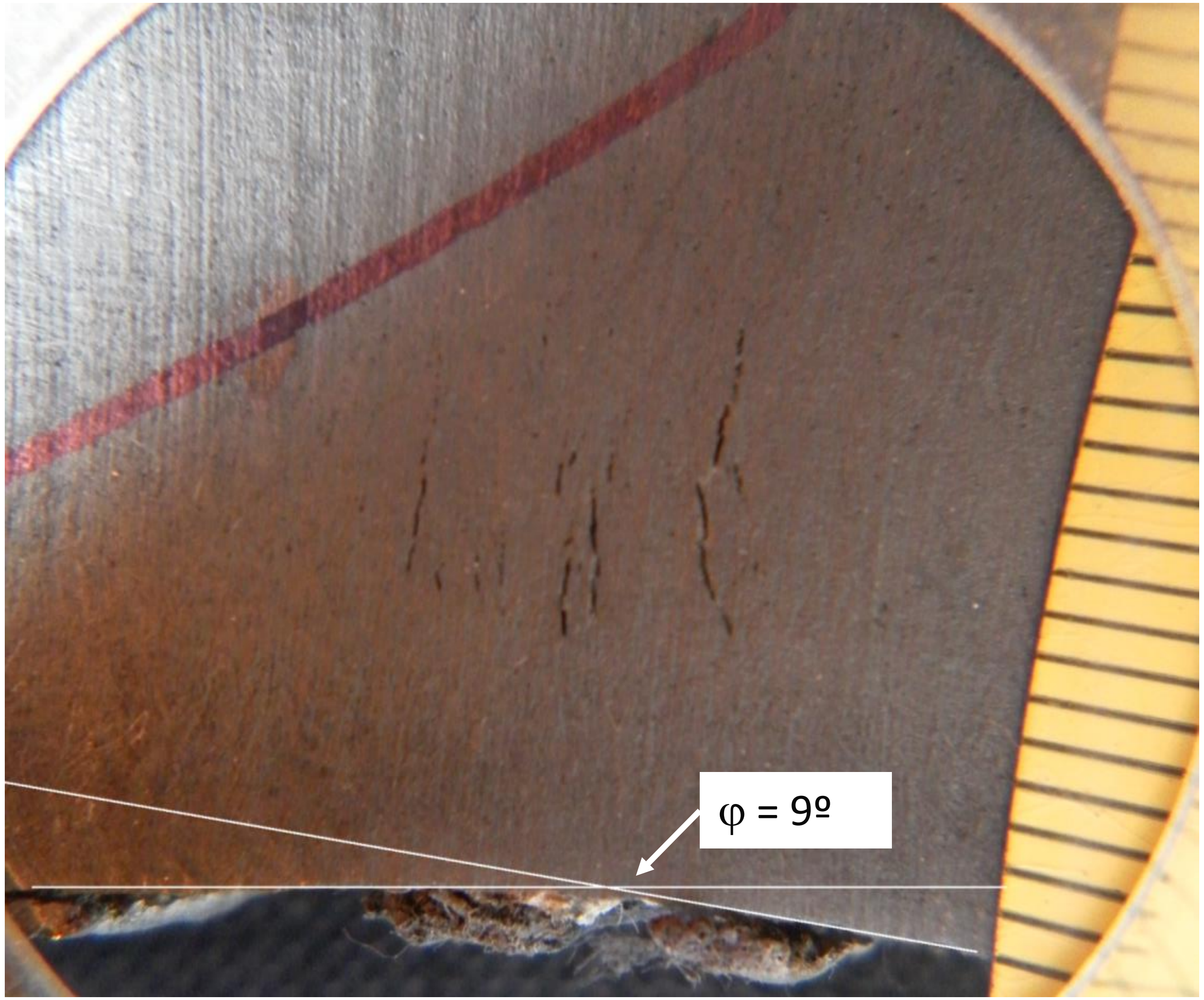
4. Internal segregation cracking classification

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.



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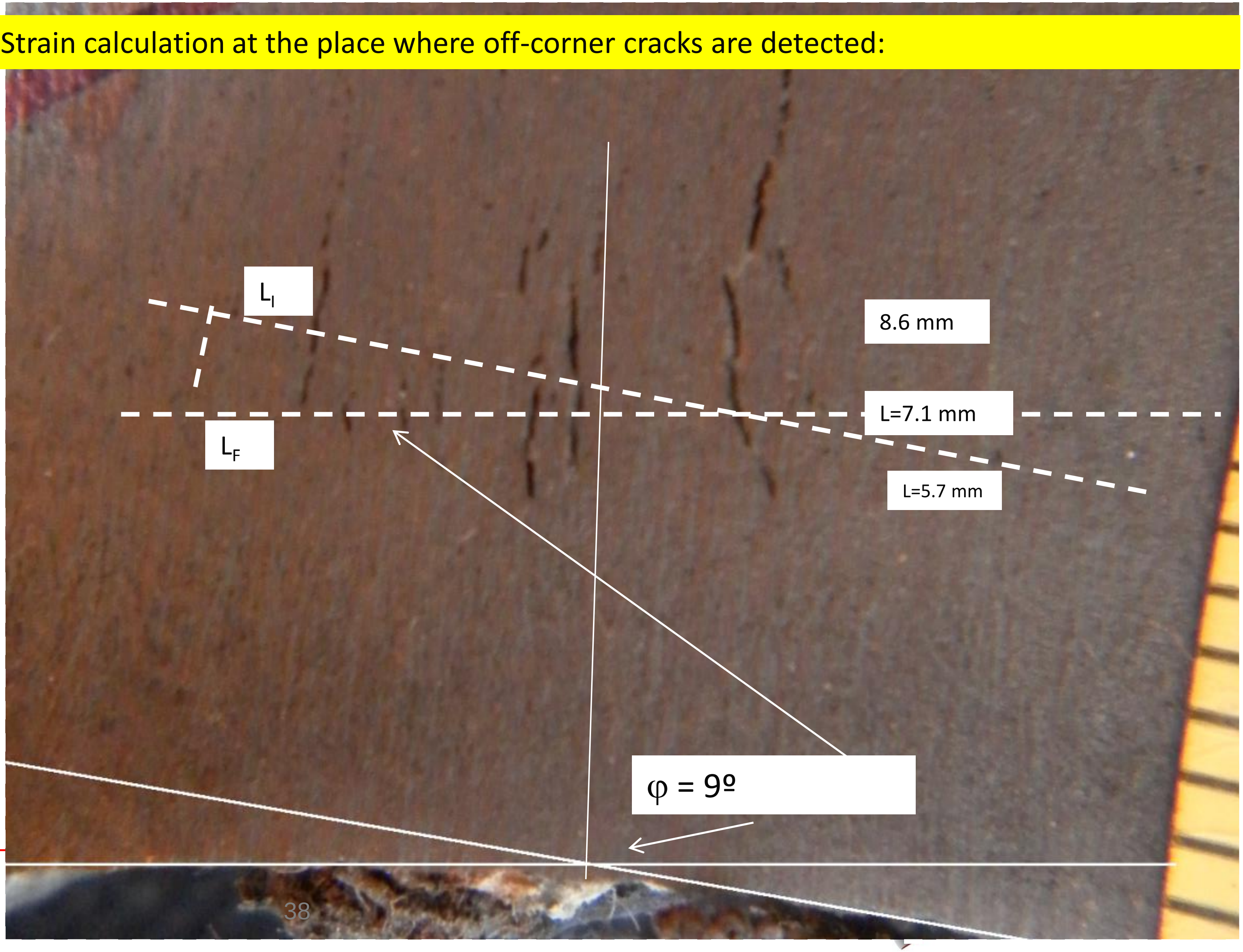
4. Internal segregation cracking classification

2. Off-Corner cracks

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



Strain at cracking position:

ε= (L_F – Li)/Li*100=(1/cos(ϕ)-1)*100

ε= 1,4%

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

4. Internal segregation cracking classification

2. Off-Corner cracks

Off-corner cracking major causes

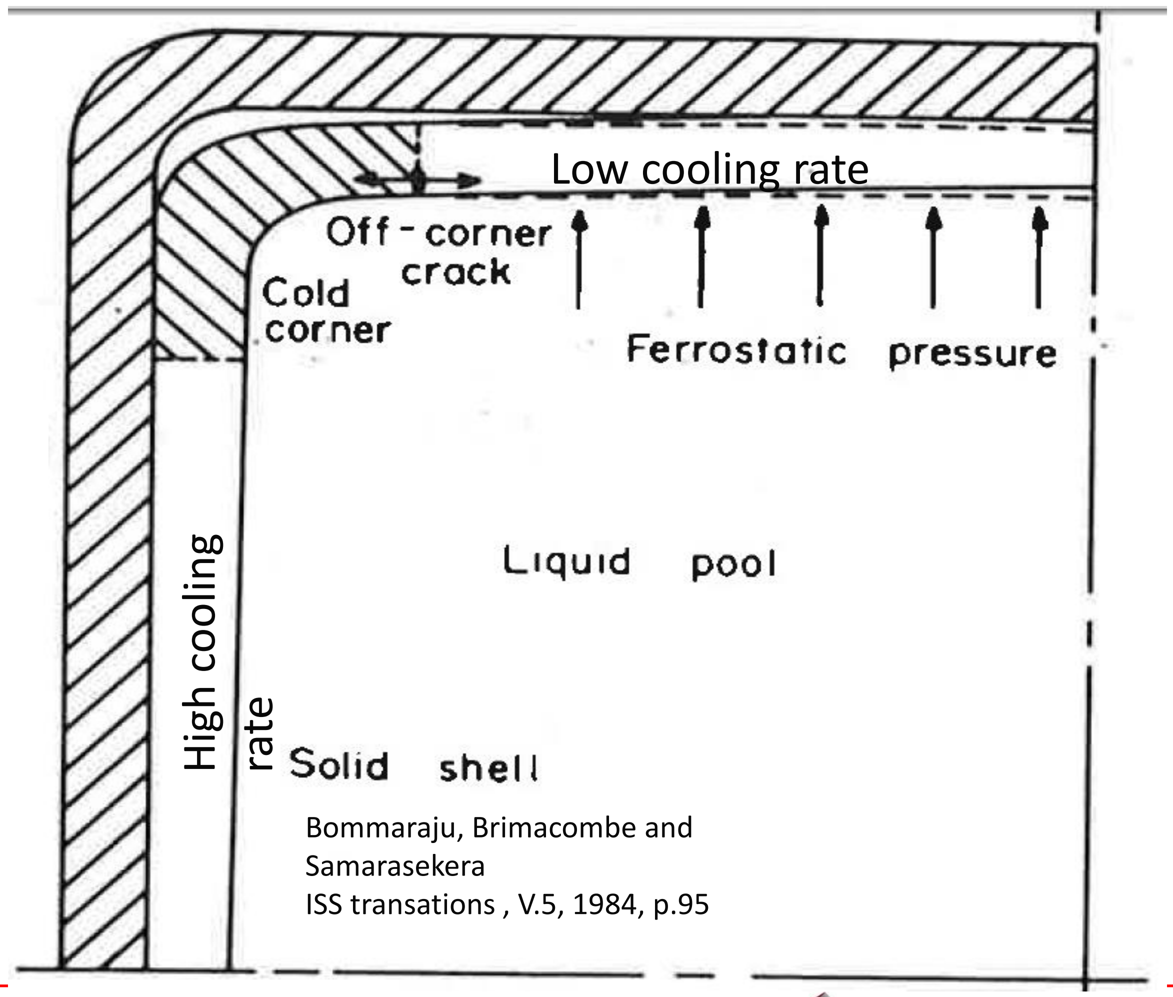
a) Differences in the mould cooling among billet faces.
b) Too thin billet solid shell at the exit of the mould.
c) Too big solid shell/mold interaction.

4. Internal segregation cracking classification

2. Off-Corner cracks

a) 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.



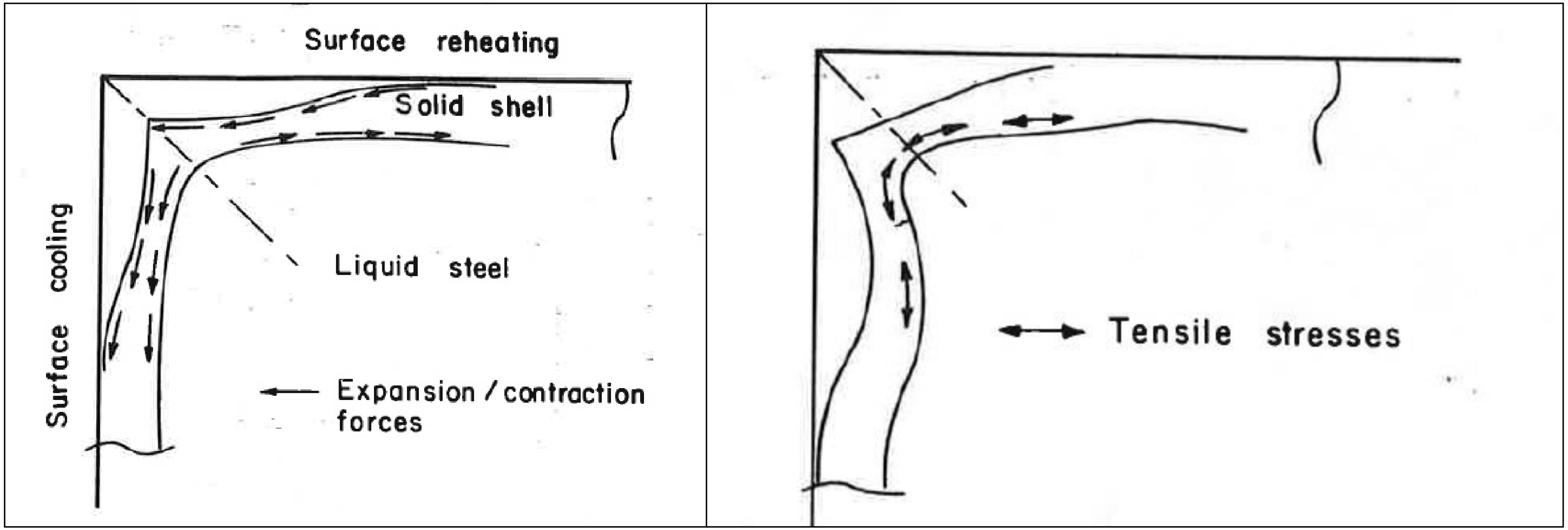
Bommaraju, Brimacombe and Samarasekera
ISS transations , V.5, 1984, p.95

4. Internal segregation cracking classification

2. Off-Corner cracks

a) Off-corner cracking major causes: Differences in the mould cooling among billet faces

Twist of the billet corner due to reheating of one billet face and cooling of the adjacent one.



Bommaraju, Brimacombe and Samarasekera
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4. Internal segregation cracking classification

2. Off-Corner cracks

b) 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.

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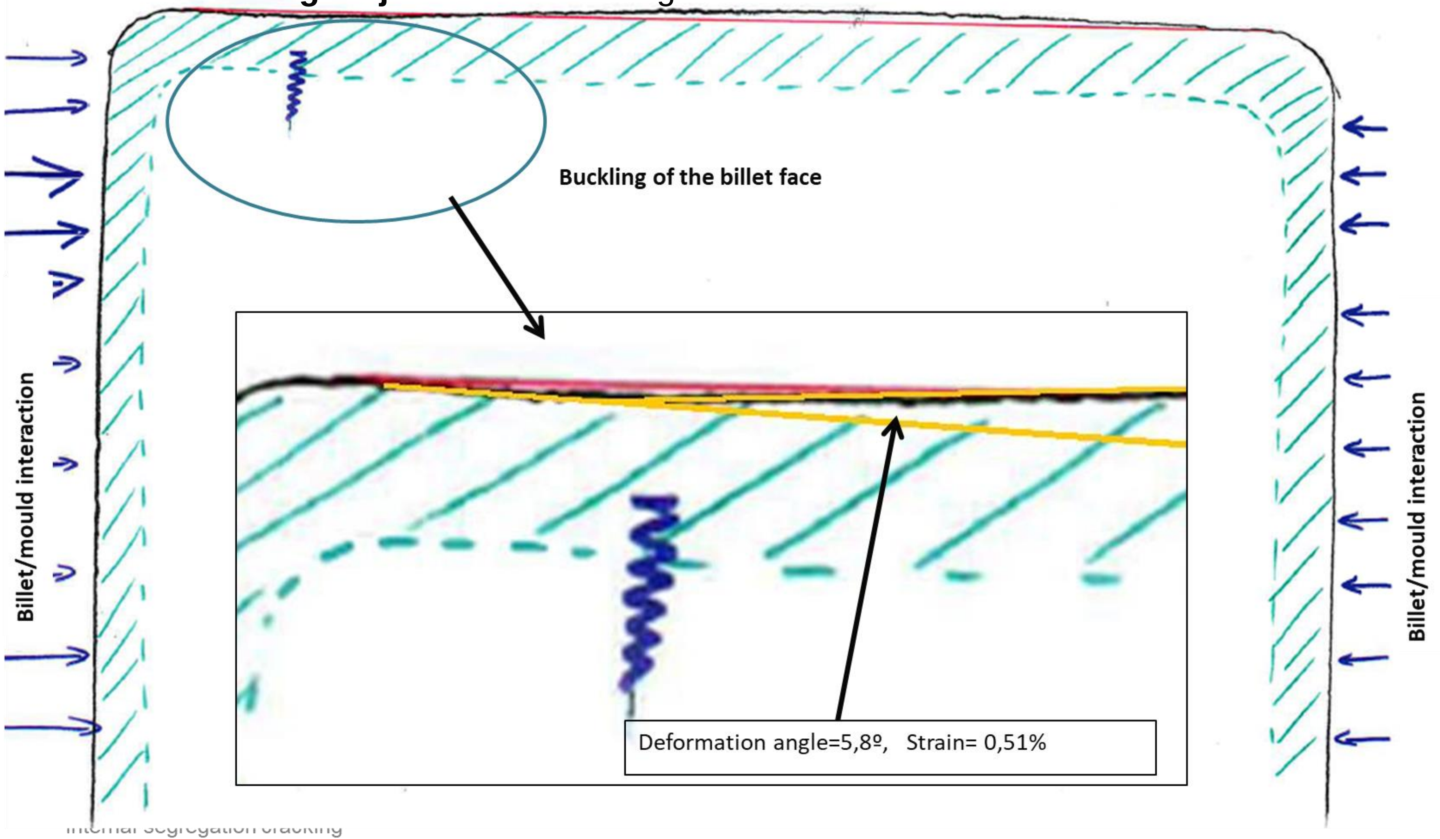
4. Internal segregation cracking classification

2. Off-Corner cracks

c) 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.

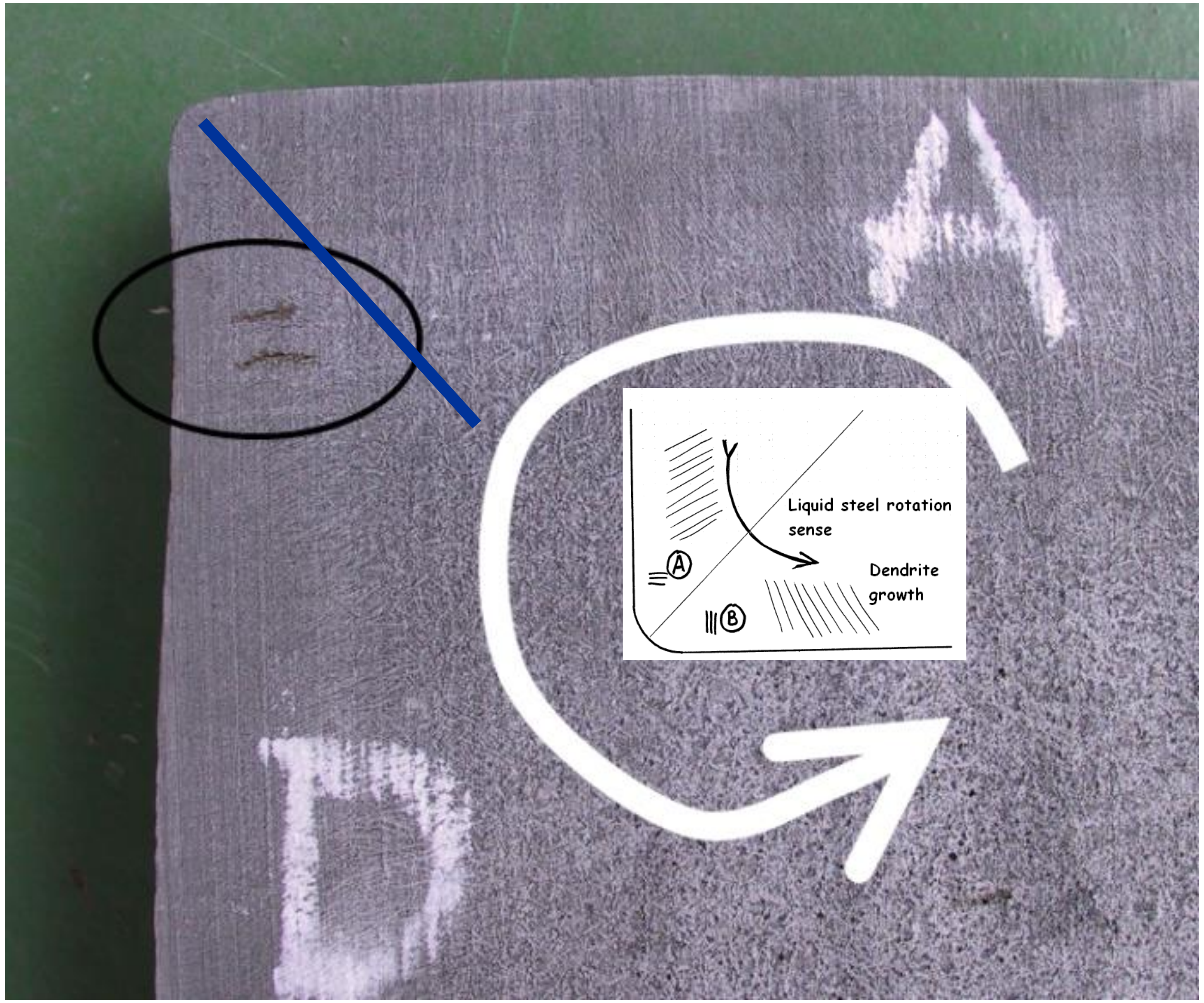
4. Internal segregation cracking classification

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

2. Off-Corner cracks: Influence of electromagnetic stirrer (EMS) on the off-corner cracking



Presence of off-corner cracking in the side of the billet corner against the EMS induced liquid flow.

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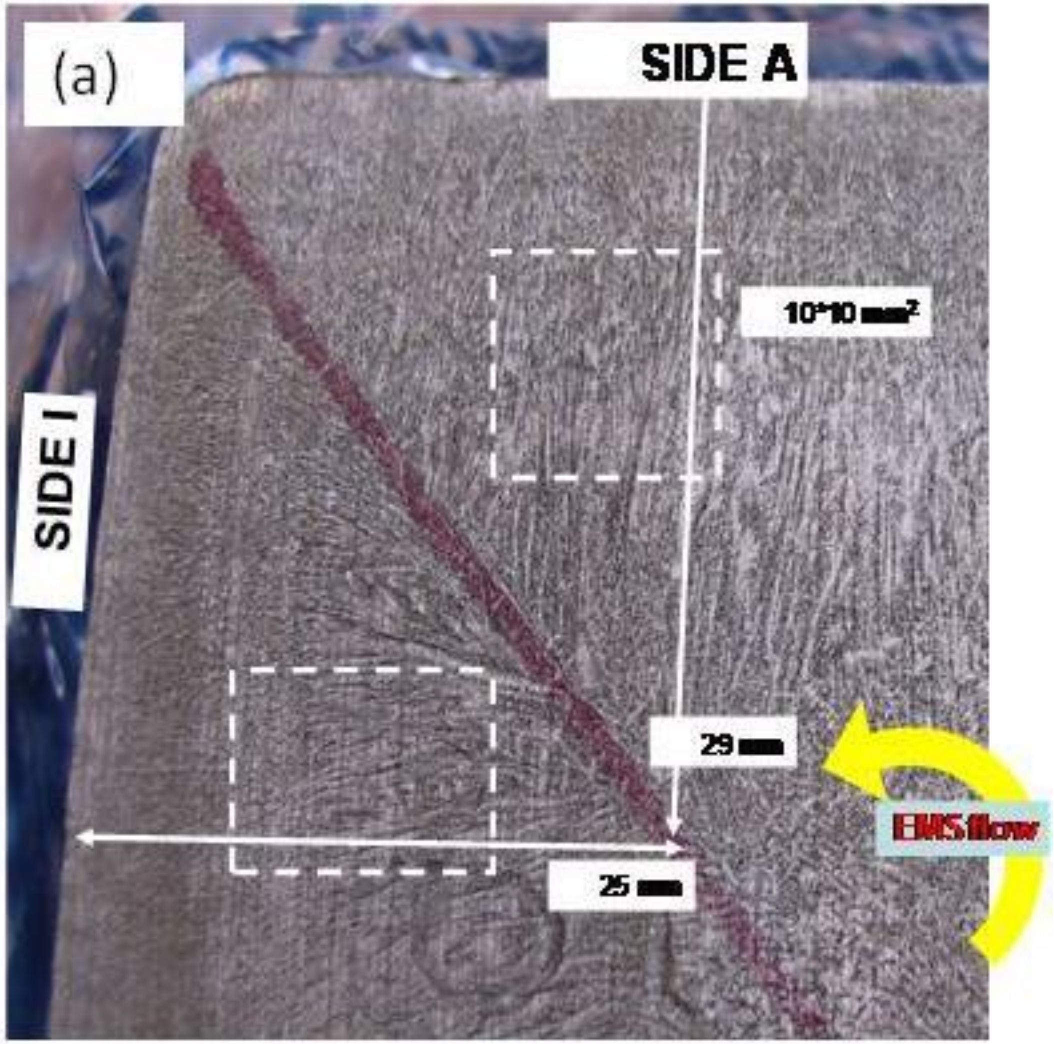
4. Internal segregation cracking classification

2. Off-Corner cracks: Influence of electromagnetic stirrer (EMS) on the off-corner cracking



There is a lack of symmetry in the solidification microstructure at the billet corner. The crystal growth length is 25 mm at the corner side against the EMS induced liquid flow and in the other side 29 mm. Therefore the difference in the crystal growth due to EMS is 14%.

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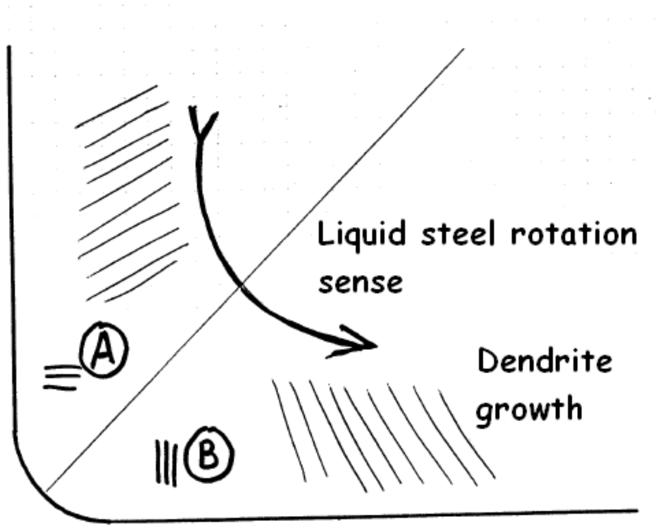
4. Internal segregation cracking classification

2. Off-Corner cracks: Influence of electromagnetic stirrer (EMS) on the off-corner cracking

The first statistical study on the influence of EMS on off-corner cracking was made at Sidenor in 1986. Other statistical studies were made afterwards. All of them shown that the probability for the OCC to be present in the corner side against liquid flow is higher than in the other billet face. The cause of this result may be related to the lower solid shell thickness growth of this corner side with respect to the other one.

Statistical study of the influence of EMS on Off-corner cracking

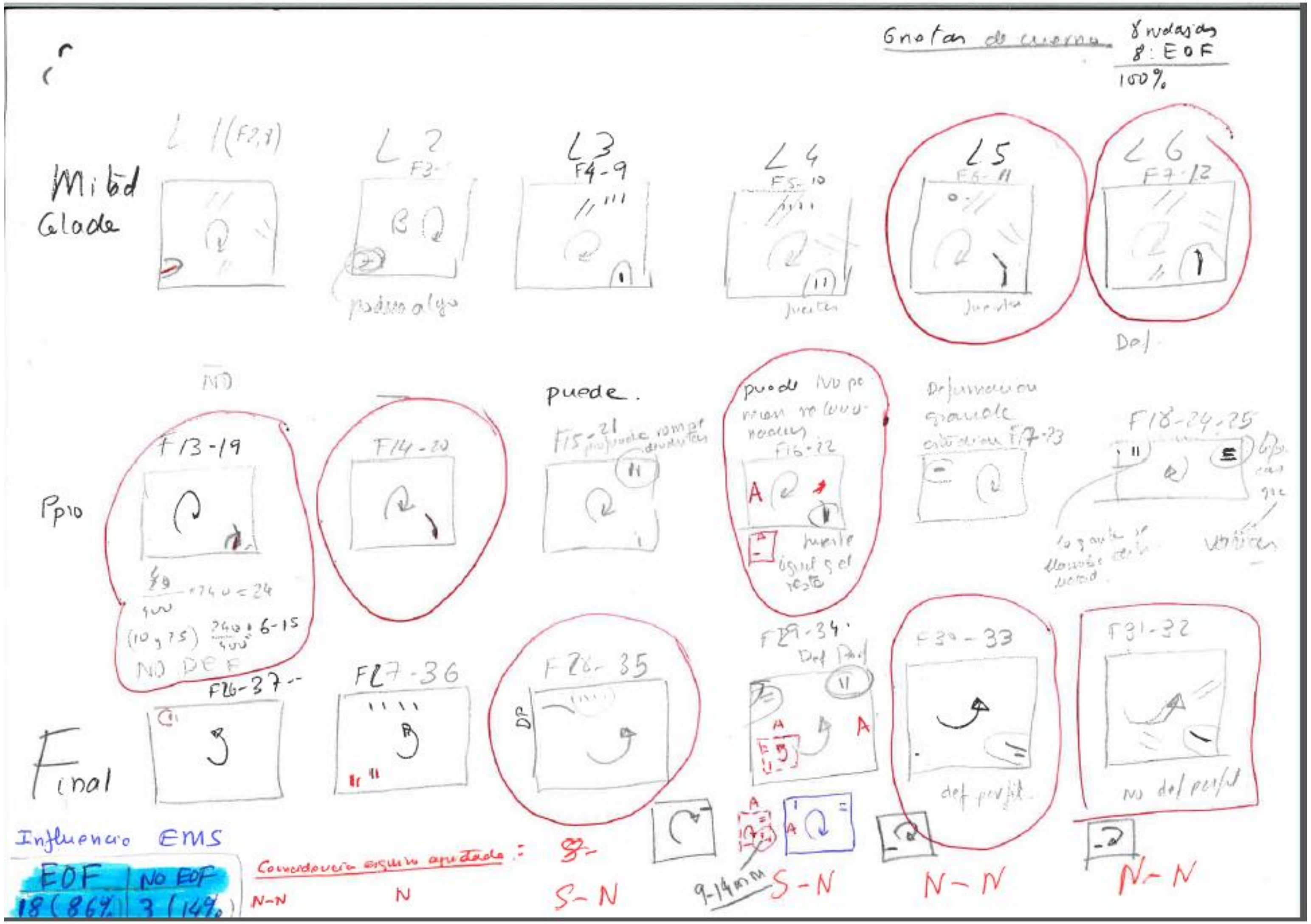


	1st statistical study 1986
Number of heats	24
Number of billet transversal samples	127
Cracks in the corner side against liquid flow	78 (62%)
Cracks in the corner side not against liquid flow	49 (38%)

4. Internal segregation cracking classification

2. Off-Corner cracks: Influence of electromagnetic stirrer (EMS) on the off-corner cracking

18 slices study of 21NiMoCr6EJ heat, prone to crack apparition (MSC=0,85). Between 21 cracked corners, 18 of them were present at the billet side which stands against liquid steel movement, this is the 86% of the occurrence.



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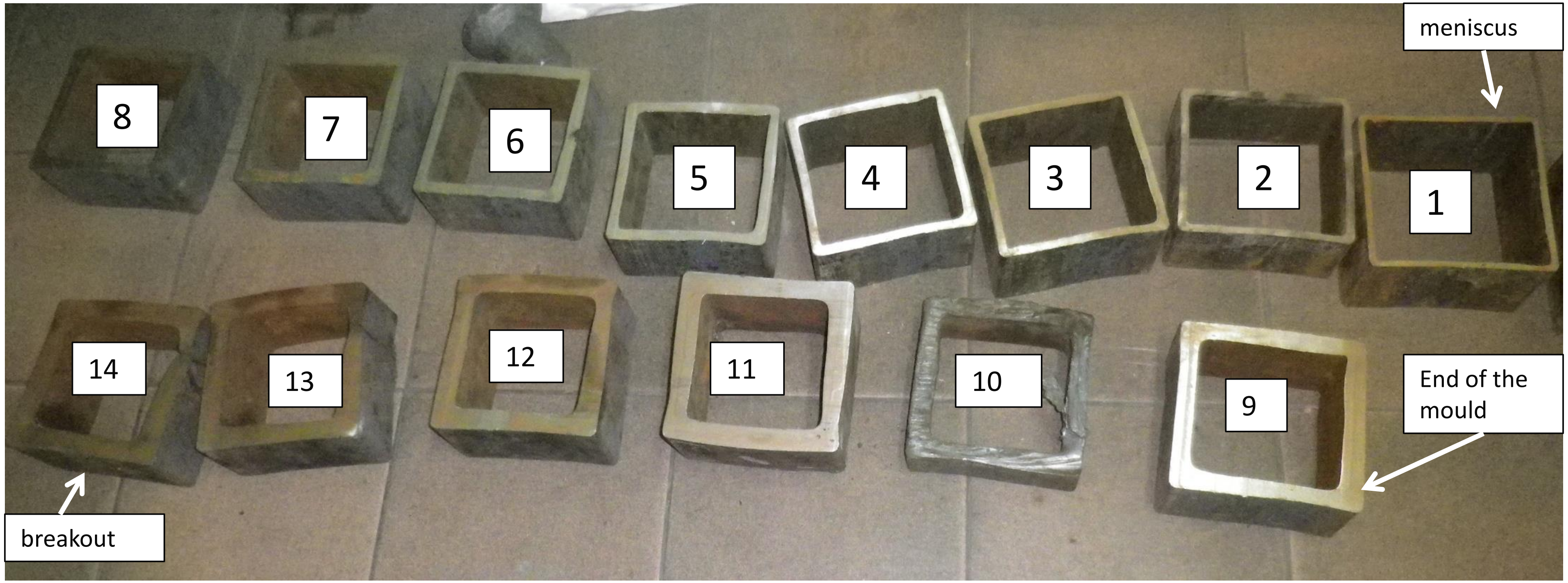
4. Internal segregation cracking classification

2. Off-Corner cracks: Influence of electromagnetic stirrer (EMS) on the off-corner cracking

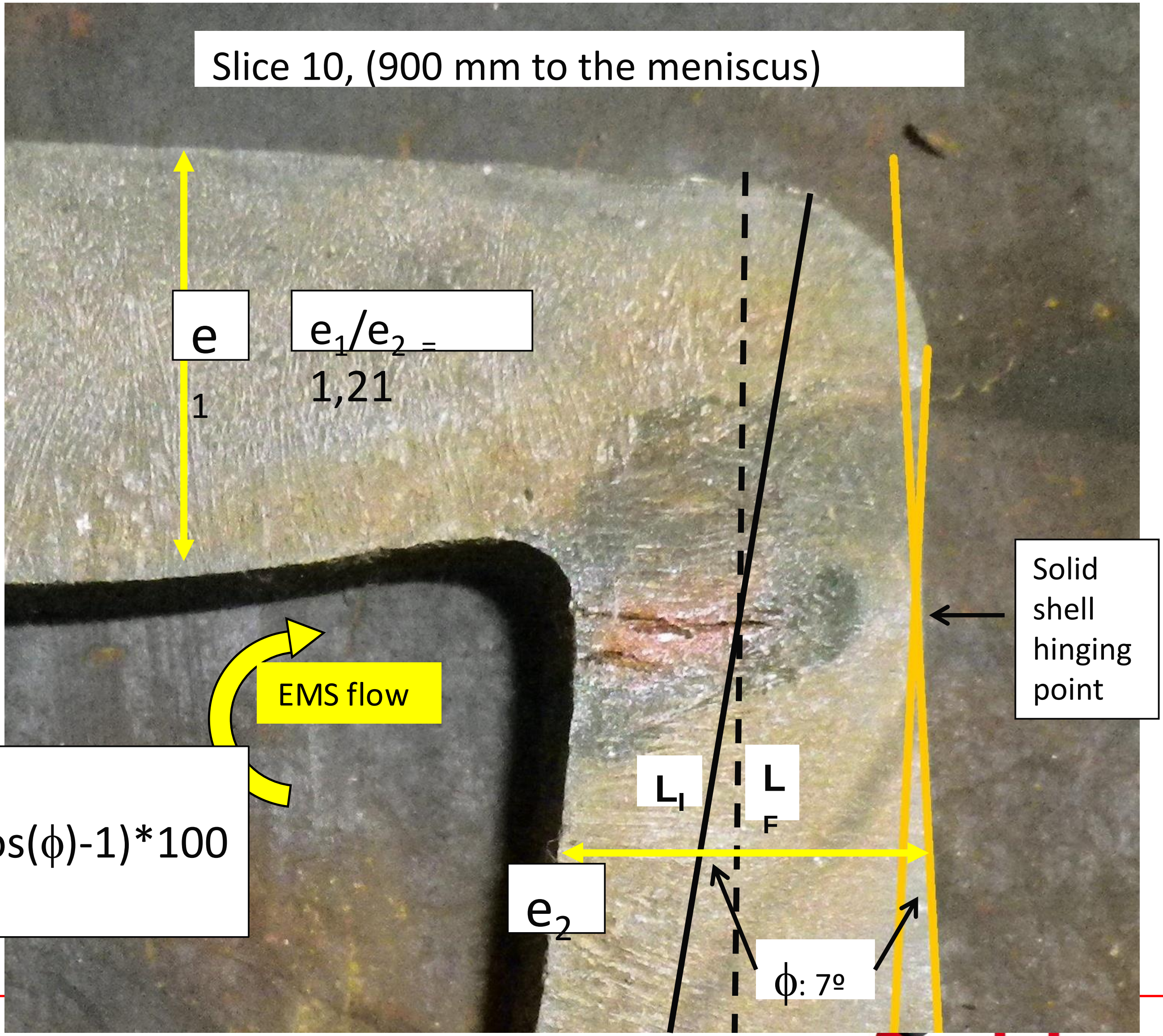
- Heat 652. 34MnB4E, 185 mm billet. Casting speed 1.75m/min.
- Strand number 1 had a breakout at a meniscus distance of 1550 mm: the liquid steel spilt through the breakout.
- The remaining strand shell is cut on 100 mm length slices.
- Off-corner cracks reaching the solid/liquid interphase were observed on the slices 5 to 10.



4. Internal segregation cracking classification

2. Off-Corner cracks: Influence of electromagnetic stirrer (EMS) on the off-corner cracking

The solid Shell thickness at the billet corner side not against the EMS induced liquid flow is 21% higher than the other billet corner side.



Strain at the solid shell:

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

$$\varepsilon = 0.75\%$$

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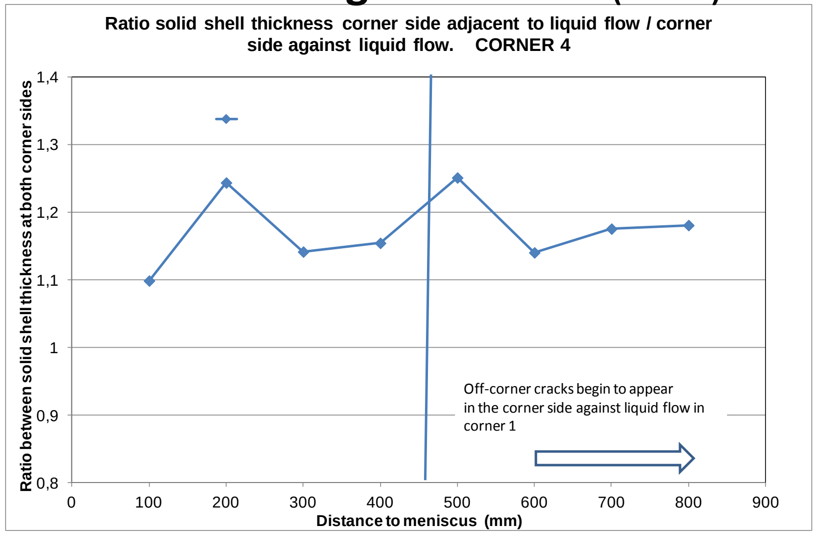
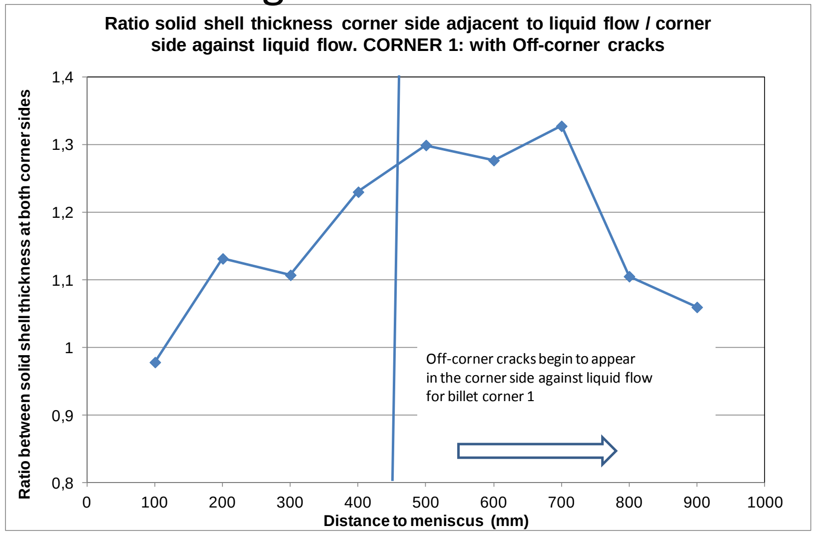
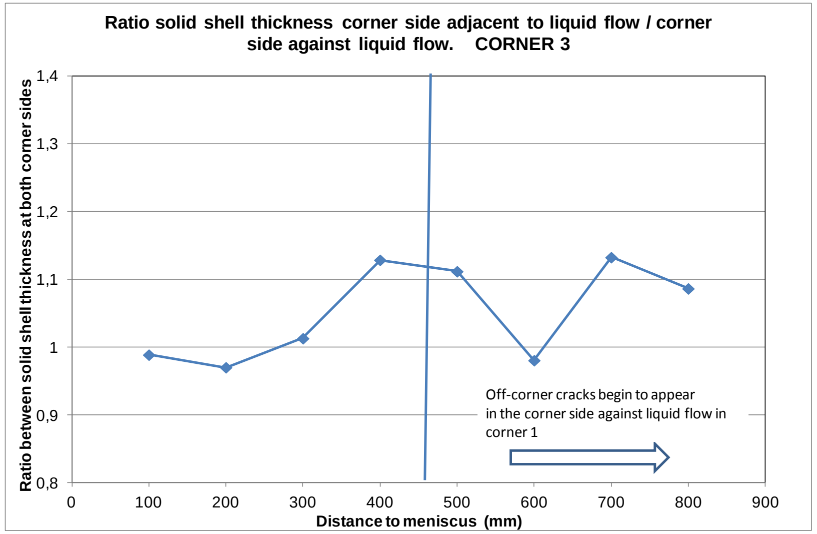
4. Internal segregation cracking classification

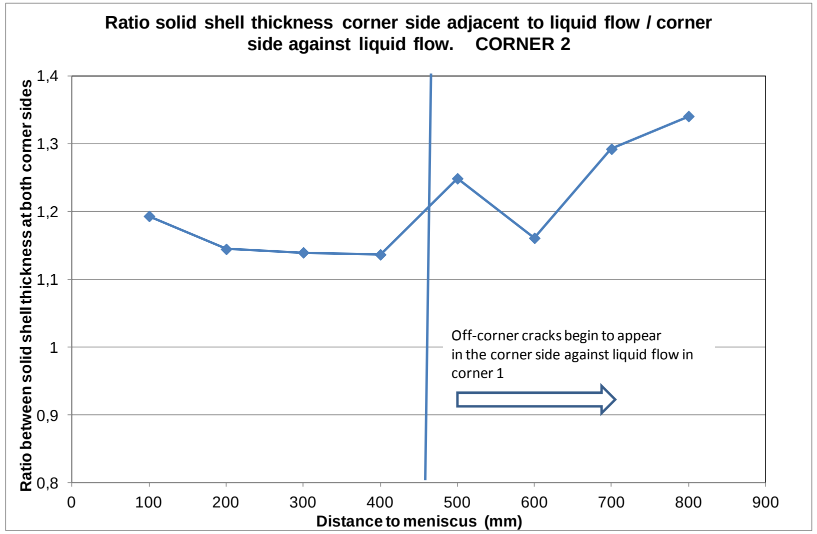
2. Off-Corner cracks: **Influence of electromagnetic stirrer** (EMS) on the off-corner cracking

A calculation was carried out of the solid shell thickness ratio between both sides of the corner for all the breakout slices, and for all the corners. The figures show that it is a general effect: the corner side which is not against the EMS induced liquid flow is 20% thicker than the other side.
On the slices nearer the meniscus, this ratio is lower for some corners, which make sense because of the lower influence of the EMS at this area.





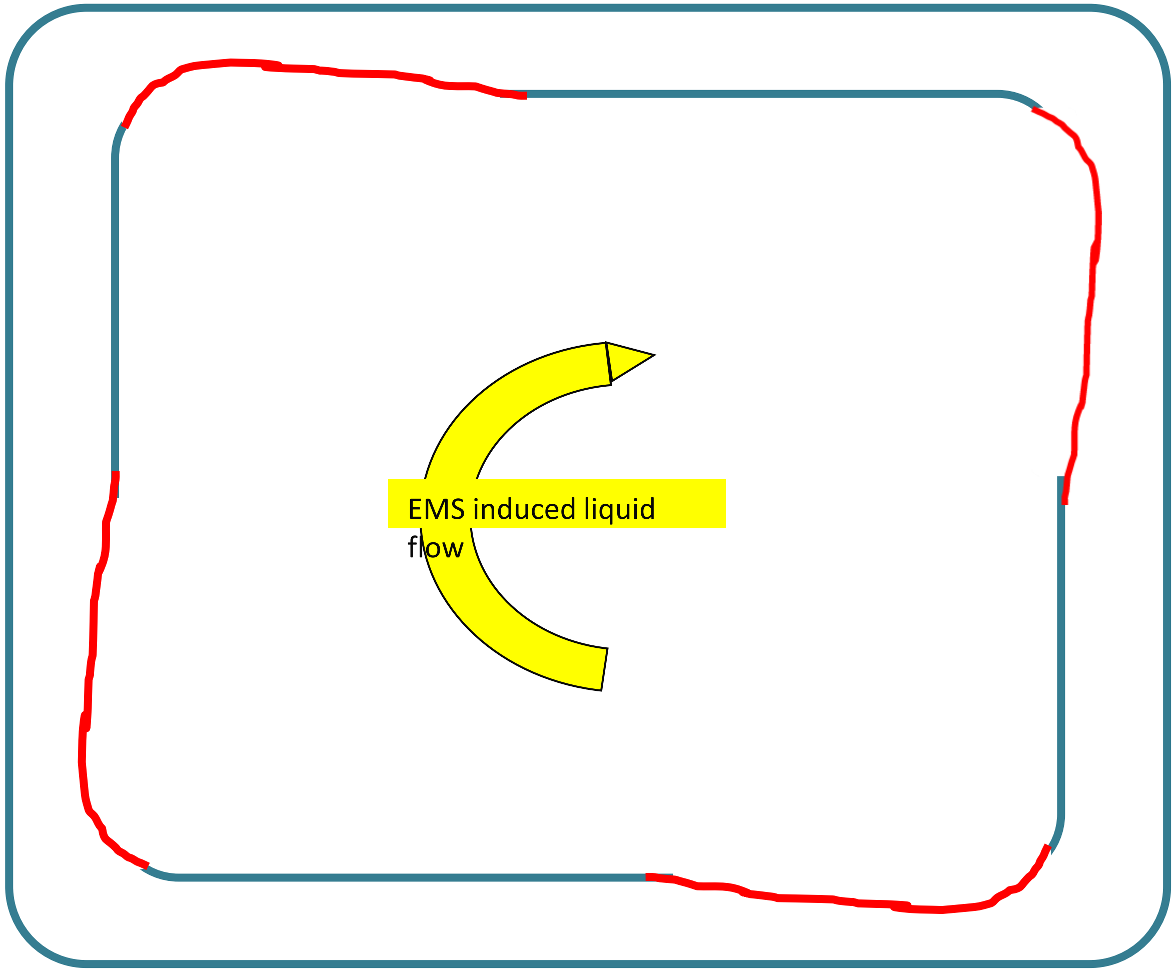




4. Internal segregation cracking classification

2. Off-Corner cracks: **Influence of electromagnetic stirrer** (EMS) on the off-corner cracking

Sketch of the solid
Shell thickness for the
breakout slices



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4. Internal segregation cracking classification

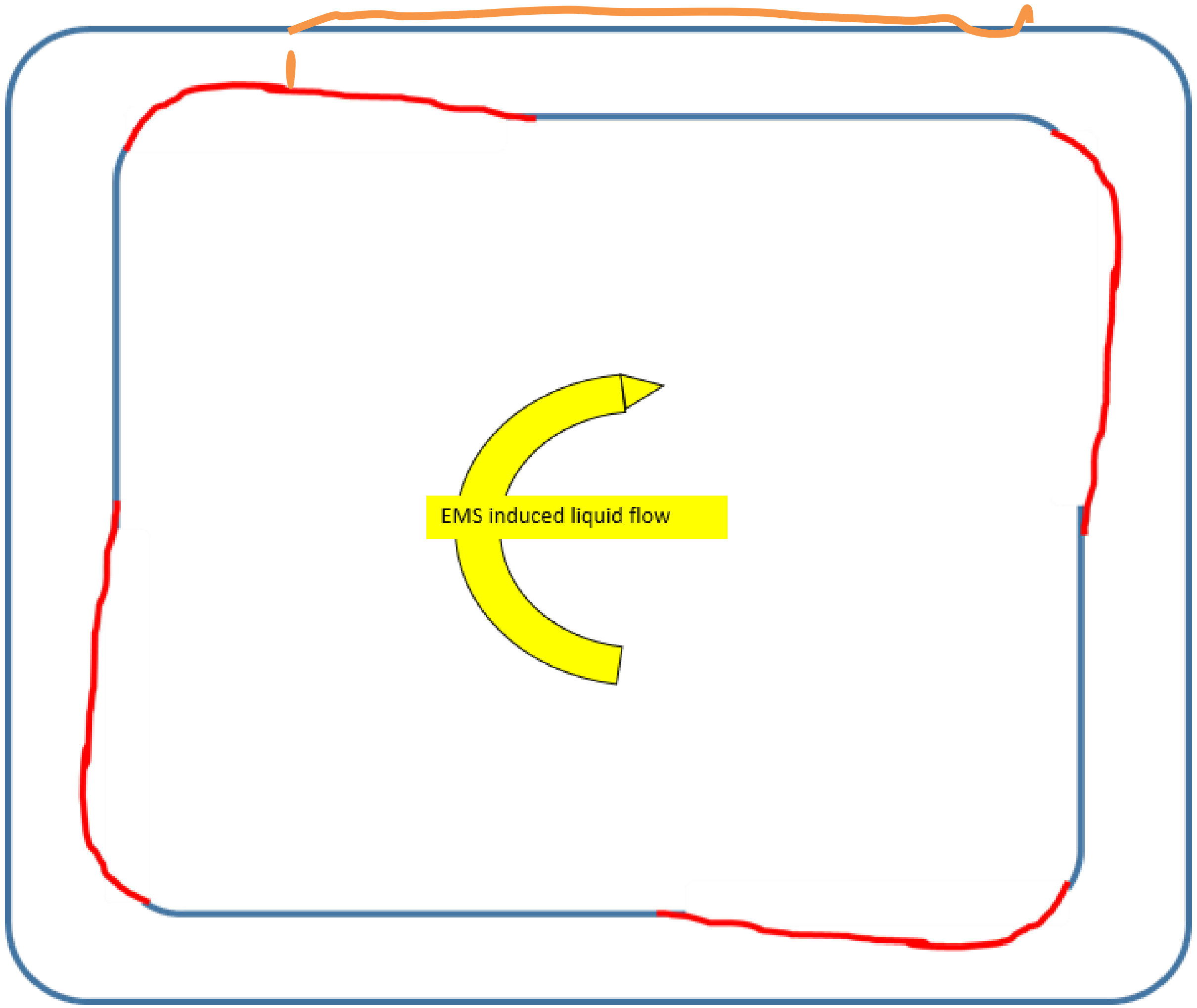
2. Off-Corner cracks: Influence of electromagnetic stirrer (EMS) on the off-corner cracking

Relationship between the shape of the solid shell thickness with EMS induced flow and the presence of off-corner cracking:

Any of the previous mentioned causes of the OCC:

1. No uniform cooling
2. Exit mould bulging
3. Big billet/mould friction

will give place to off-corner cracking on the corner side facing the EMS induced liquid flow, because it is the weakest part of the billet face. The existence of those weak zones may turn the billet more prone to cracking than other billet with a uniform shell thickness around the perimeter.



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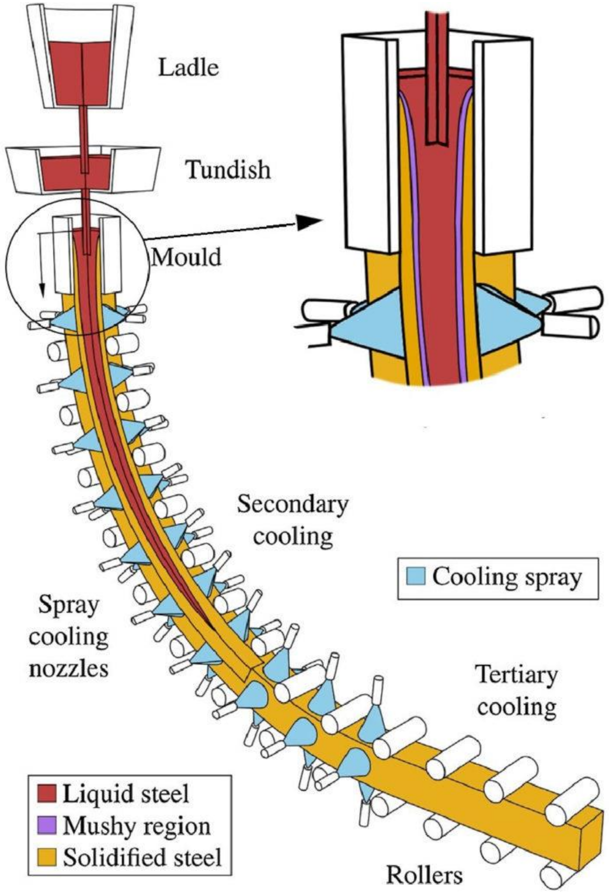
Internal segregation cracking classification

Internal defects: Near to corner cracks

Internal segregation cracking

- Chemical composition
- Strain in the solid shell
  1. Half-way cracks
  2. Off-corner cracks
  3. Near to corner cracks

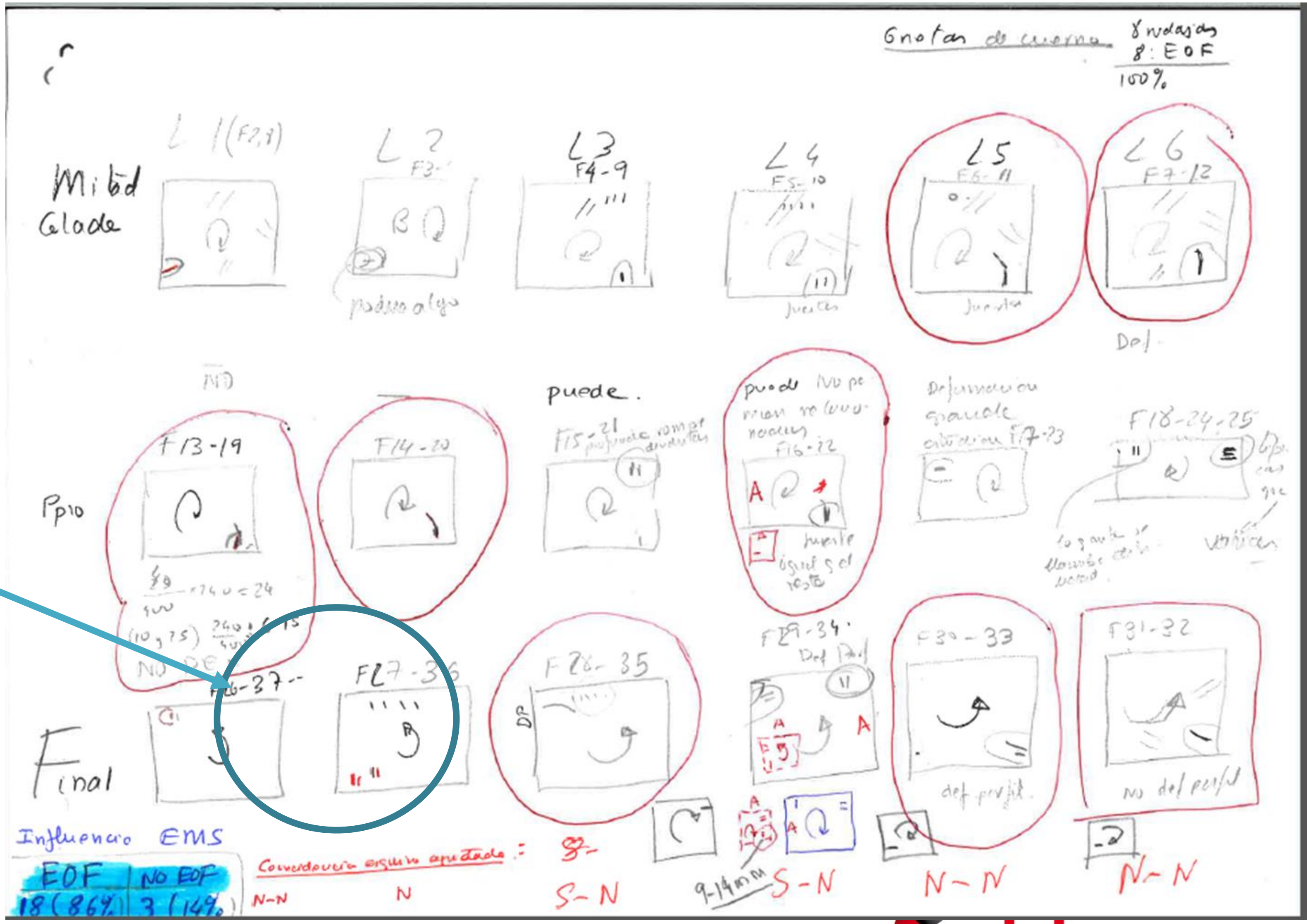


4. Internal segregation cracking classification

3. Near to corner cracking: **Practical example: 21NiMoCr6E**

MSC=0,85

This slice present in the corner two different kind of cracks



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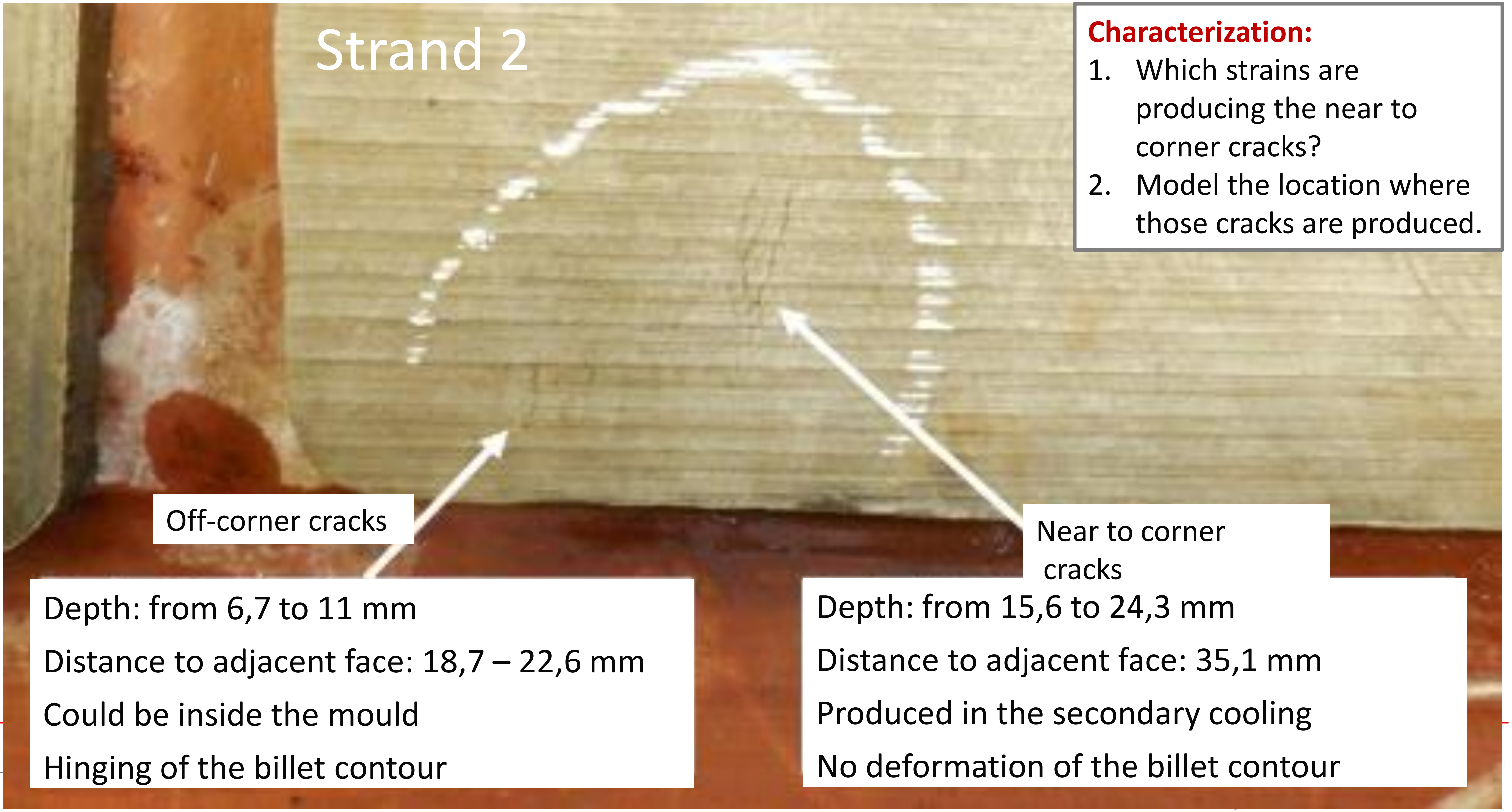
4. Internal segregation cracking classification

3. Near to corner cracking: **Practical example: 21NiMoCr6E**



Characterization:

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

Off-corner cracks

Depth: from 6,7 to 11 mm

Distance to adjacent face: 18,7 – 22,6 mm

Could be inside the mould

Hinging of the billet contour

Near to corner cracks

Depth: from 15,6 to 24,3 mm

Distance to adjacent face: 35,1 mm

Produced in the secondary cooling

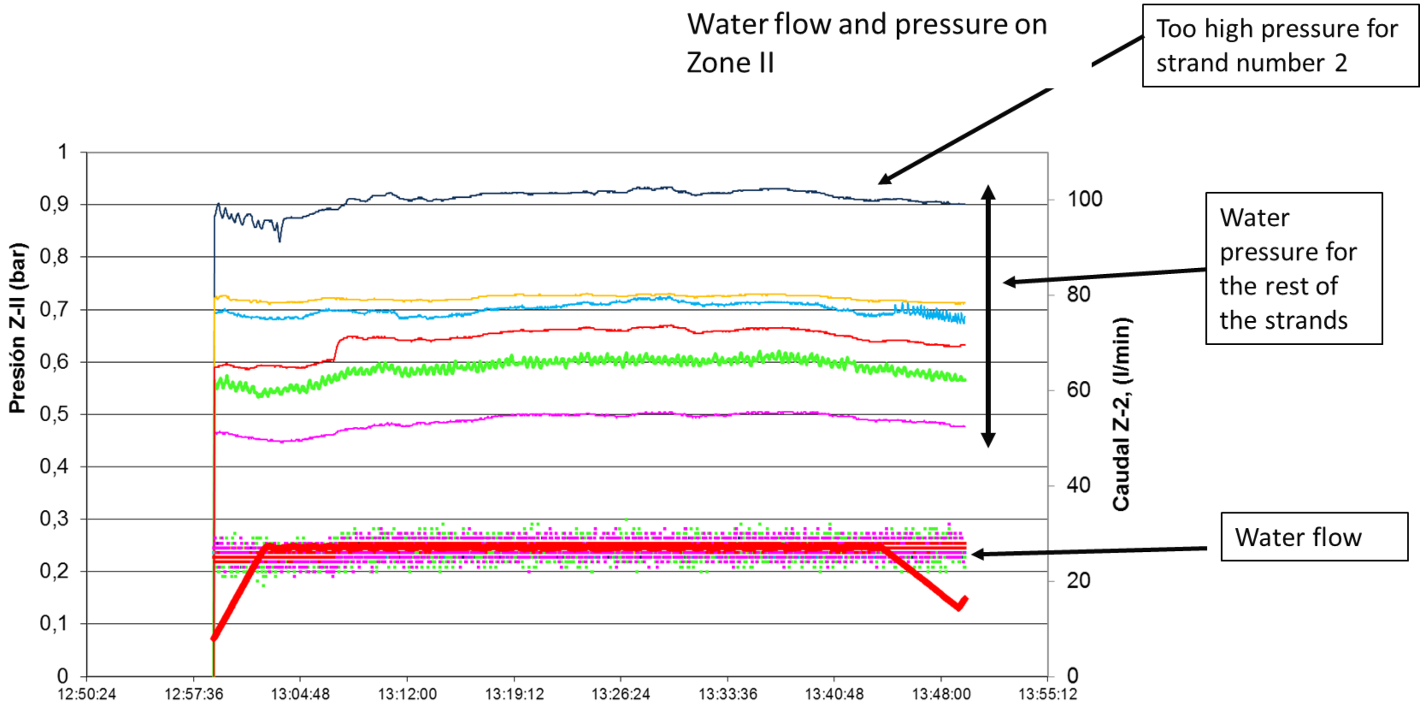
No deformation of the billet contour

4. Internal segregation cracking classification

3. Near to corner cracking: Practical example: 21NiMoCr6E

- Study of the stress producing cracks

- As the cracking is observed at 15 – 24 mm depth at the strand number 2, the cause should be some reheating at the secondary cooling.
- An increase of the pressure of the Zone II water cooling was observed for the present case. That increase is most probably related a nozzle plugged at the secondary cooling zone.



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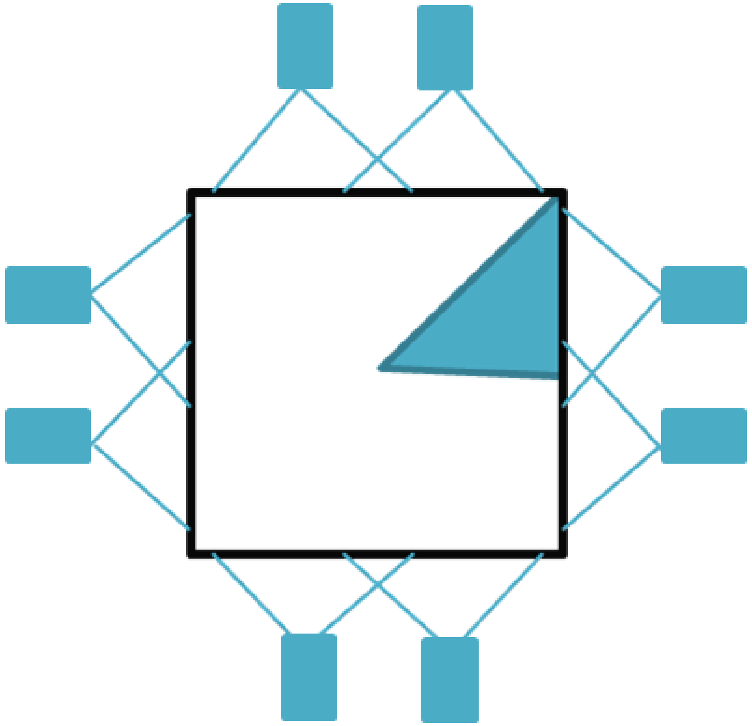
4. Internal segregation cracking classification

3. Near to corner cracking: Practical example: 21NiMoCr6E

- **Study of the stress producing cracks**



Transversal view of the Zone II secondary cooling design

The nozzle plugged would affect a quarter billet area, as the one indicated in the figure. The reheating due to lack of cooling could produce internal cracking at a distance to the adjacent billet face in the range of the 36 mm observed cracking. The depth of the cracks has been investigated by means of 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.

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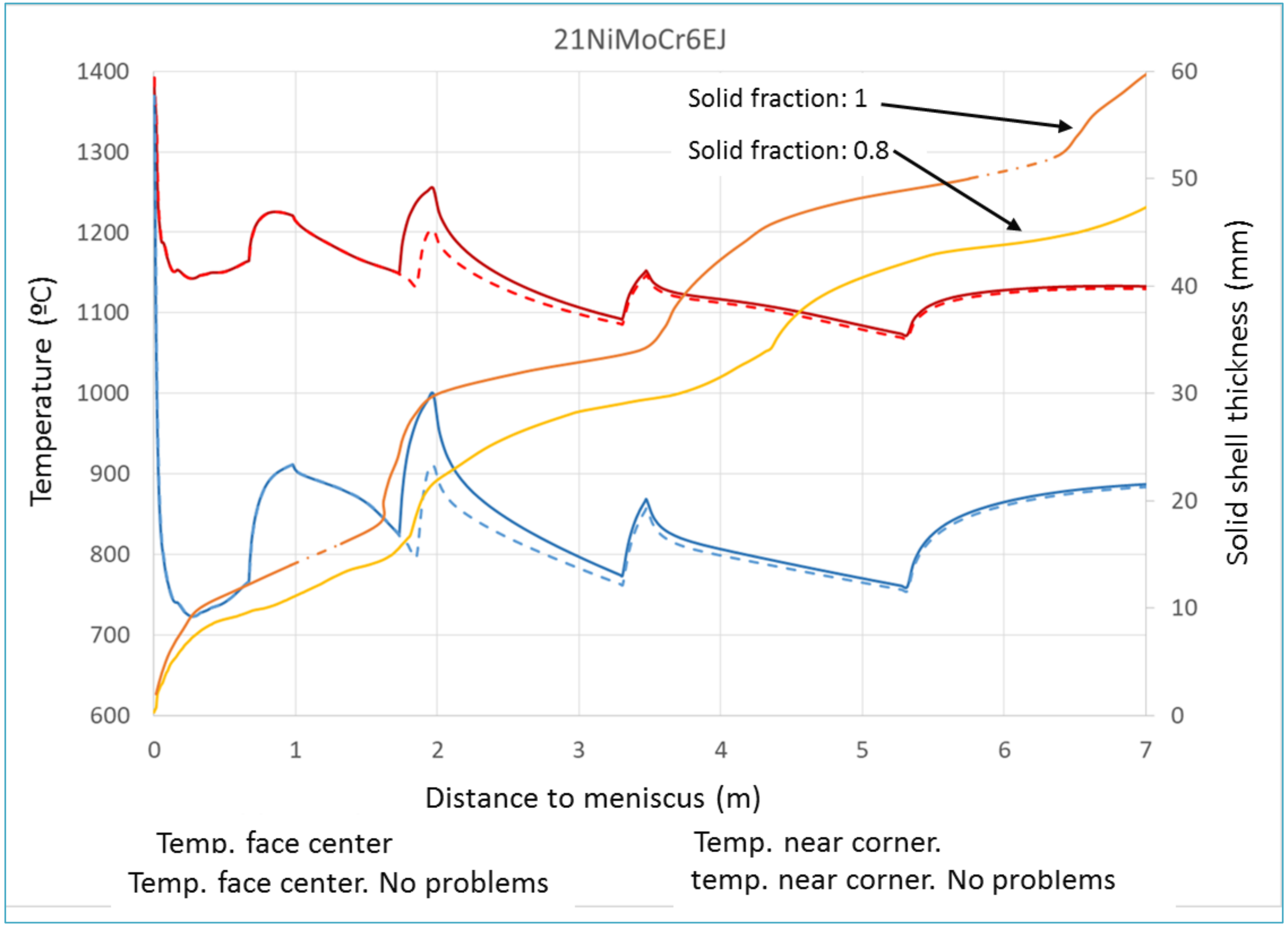
4. Internal segregation cracking classification

3. Near to corner cracking: Practical example: 21NiMoCr6E

- DISTEMP simulation

The results show the temperature in the strand when there is one nozzle plugged at the last row of the secondary cooling Zone II .

It can be seen the influence of a nozzle plugged at the last row of the secondary cooling Zone II on the billet surface reheating. In the area closed to the corner, the reheating is of around 180 ºC, which will give place to an internal cracking between 15 mm and 24 mm, quite near to the depth observed in the cracked billet sample.



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5.CONCLUSIONS

5. Conclusions

1. The presence of segregation cracking is related with the presence of stresses at the solidified solid shell.
2. Cranking 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. At the mould, EMS decreases the solid shell thickness in the corner billet side against EMS induced liquid steel flow, which enhances the formation of cracking at that corner side.
7. Nozzle plugging at the secondary cooling Zone II 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.