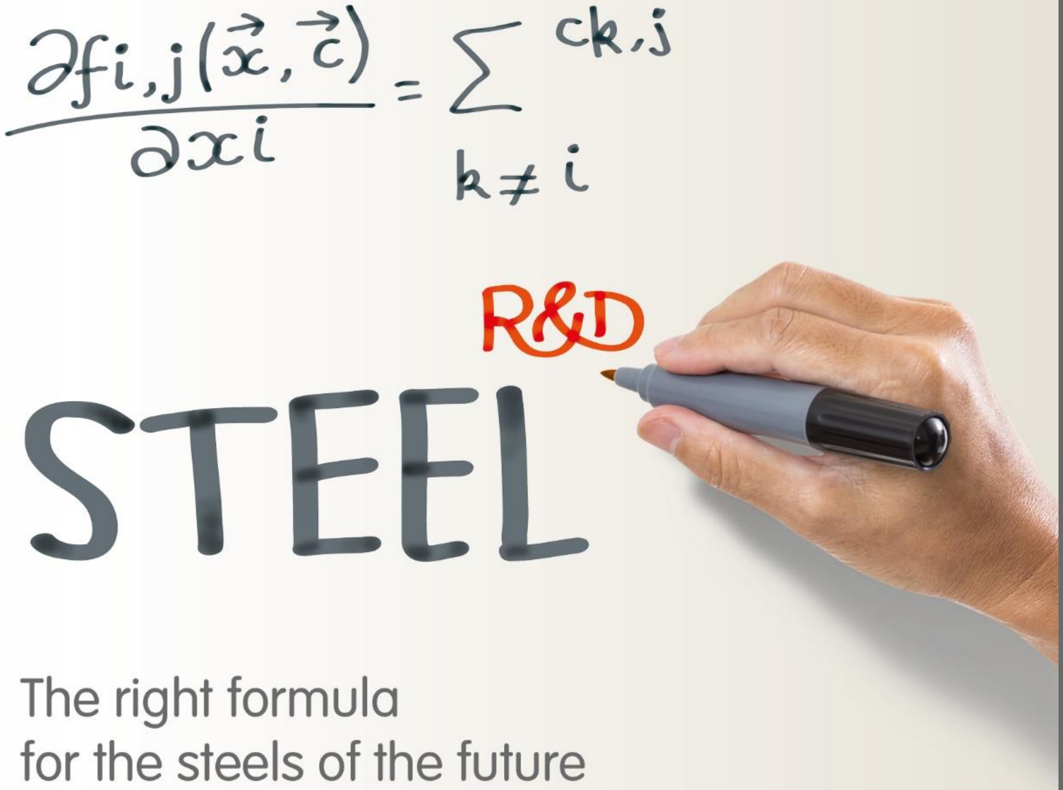
Thermal heterogeneities from the furnace to the coiler

17/06/2021 – JL. Borean



Consequences of the thermal heterogeneities?

- Surface defects
  - Oxidation favored on the hottest points
- Flatness
  - Temperature gradients
- Metallurgical (with or without a link with a surface defect)
  - Mechanical heterogeneities
- On the whole route
  - Pickling
  - Cold rolling
  - Annealing

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Origin of the thermal heterogeneities

- Casting
- Reheating furnace
- Roughing mill and width reduction
- Rolling direction
- Coil box
- Finishing mill
- Cooling and Run-Out Table
- Coil cooling

Casting

- Not well documented (limited publications)
- Some assessments are easier to do now on casted slabs
- Link with surface properties of the casted slabs and defects/issues observed at the HSM
  - Surface heterogeneities not always cleaned by the reheating furnace and the furnace descaling
    - Top/Bottom: common
    - Along the slabs: regularly observed
  - These surface heterogeneities leading to thermal heterogeneities

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Reheating furnace

- 3D modeling of the reheating furnace
  - Walking beam
  - Cooling of the skids
- Constant parameters used for the calculations
  - Low carbon steel
  - Load
    - 5 slabs (same dimensions: length, width and thickness)
    - Staggered
  - Thickness: 247mm
  - Length: 13000mm
  - Discharging temperature: 1250 °C
  - Data are extracted from the central slab
- Tested parameters
  - Width
  - Heating time
  - Distance between slabs
  - Charging temperature

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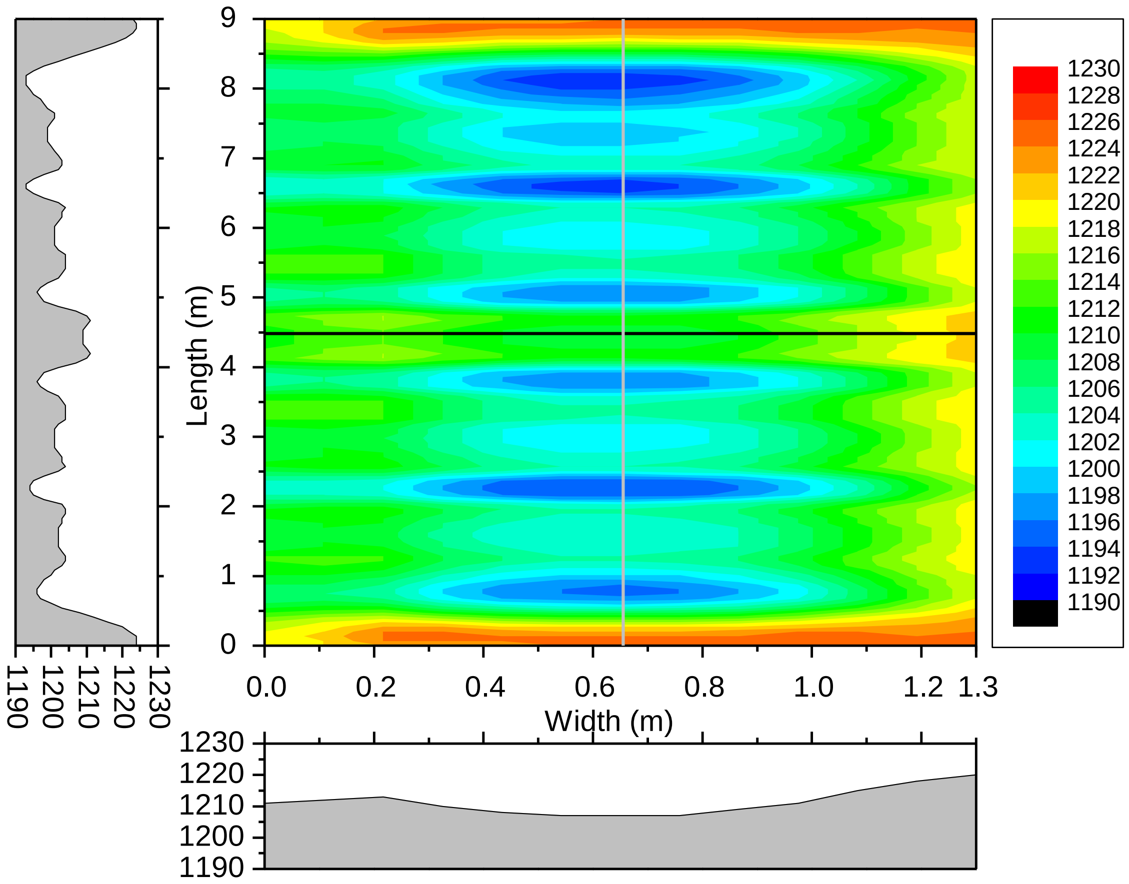
Reheating furnace

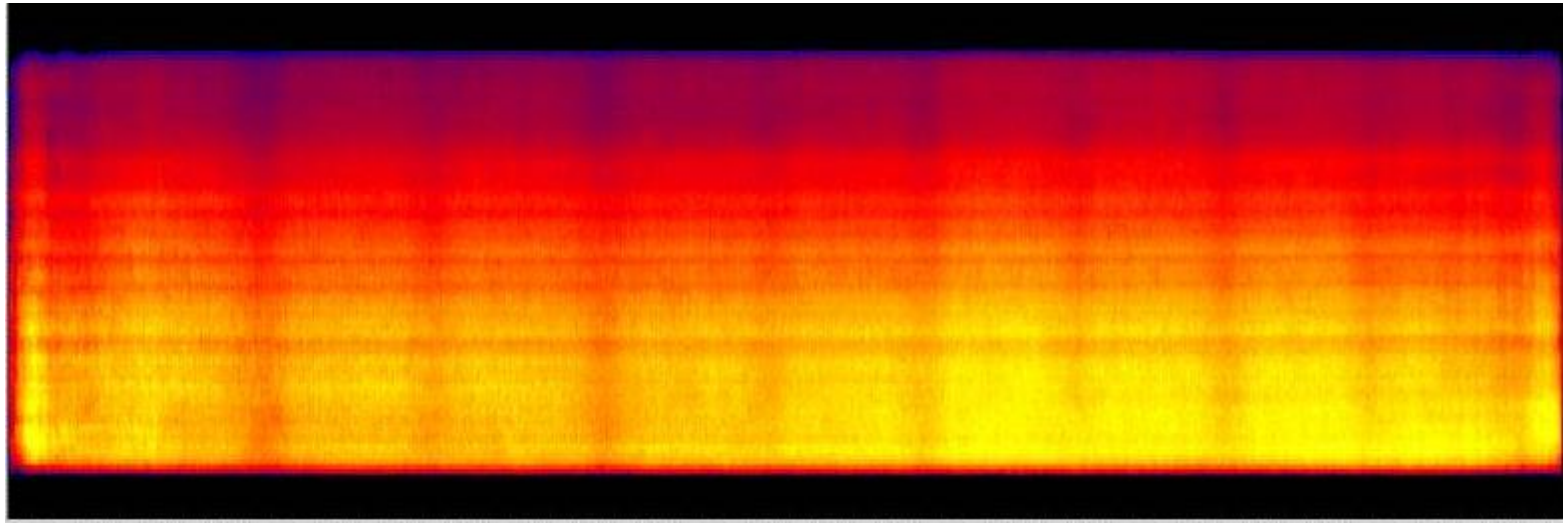
- The reheating furnace at the origin of the thermal heterogeneities



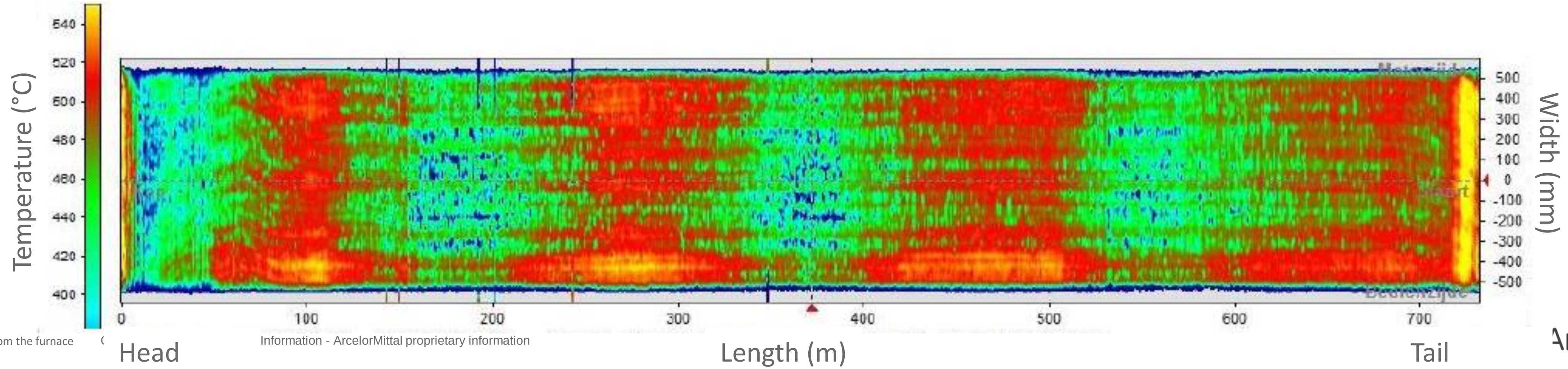
- Skid marks
- Head ant tail: overheated
- Edges
  - Underheated: operator side (door)
  - Overheated: motor side

Reheating furance
Skid marks

- Skid marks are still visible on thermal maps after the finishing mill



- And after the ROT



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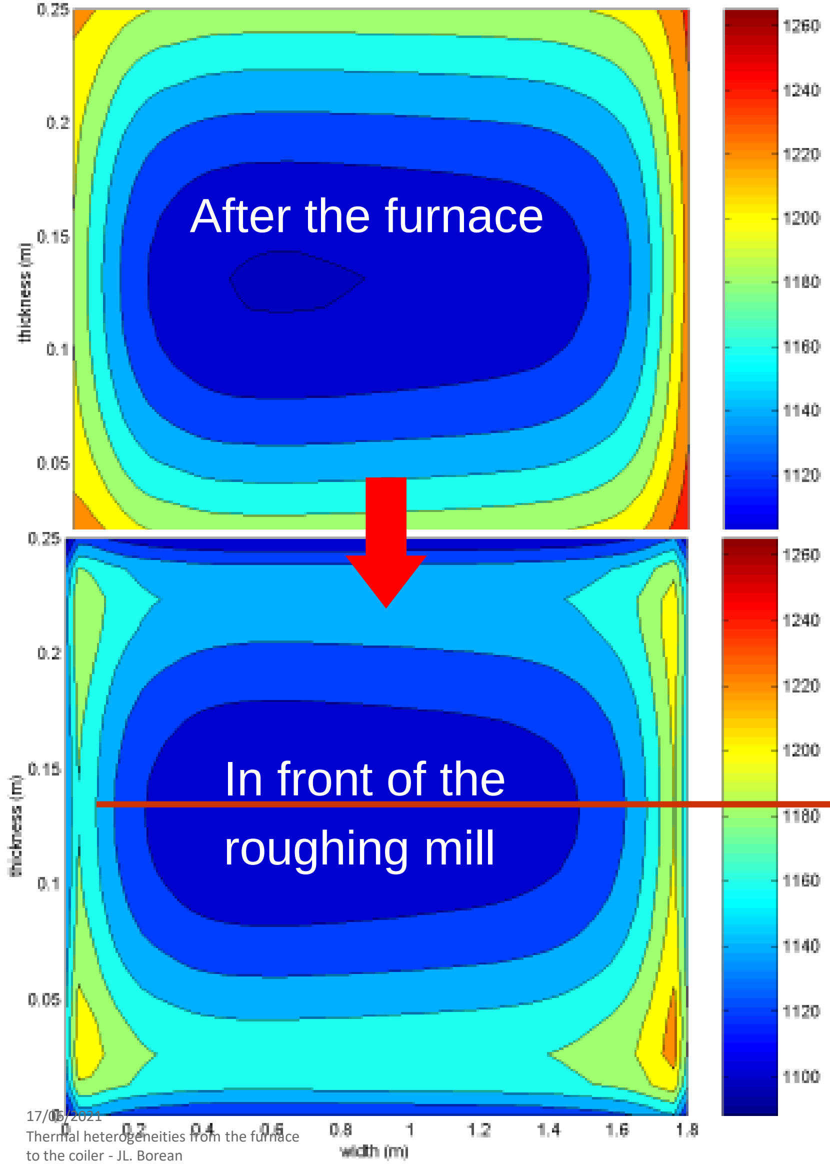
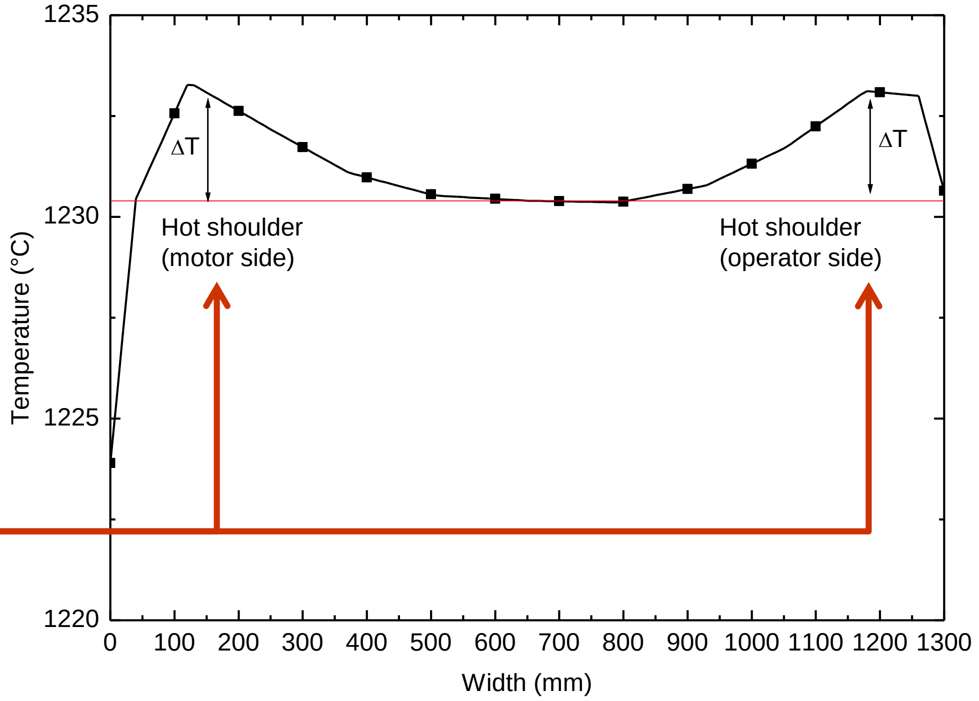
Reheating furnace
After the slab discharging, birth of the hot shoulders



- After slab discharging
  - Air cooling
  - Top/Bottom

After slab discharging and air cooling, presence of hot shoulders even on the underheated motor side



Hot shoulder: $\Delta T = T_{peak} - T_{center}$

Reheating furnace
Furnace parameters acting on the thermal heterogeneities

- Reheating time
- Space between slabs
- Hot charging
- Width of the slab
- Loading

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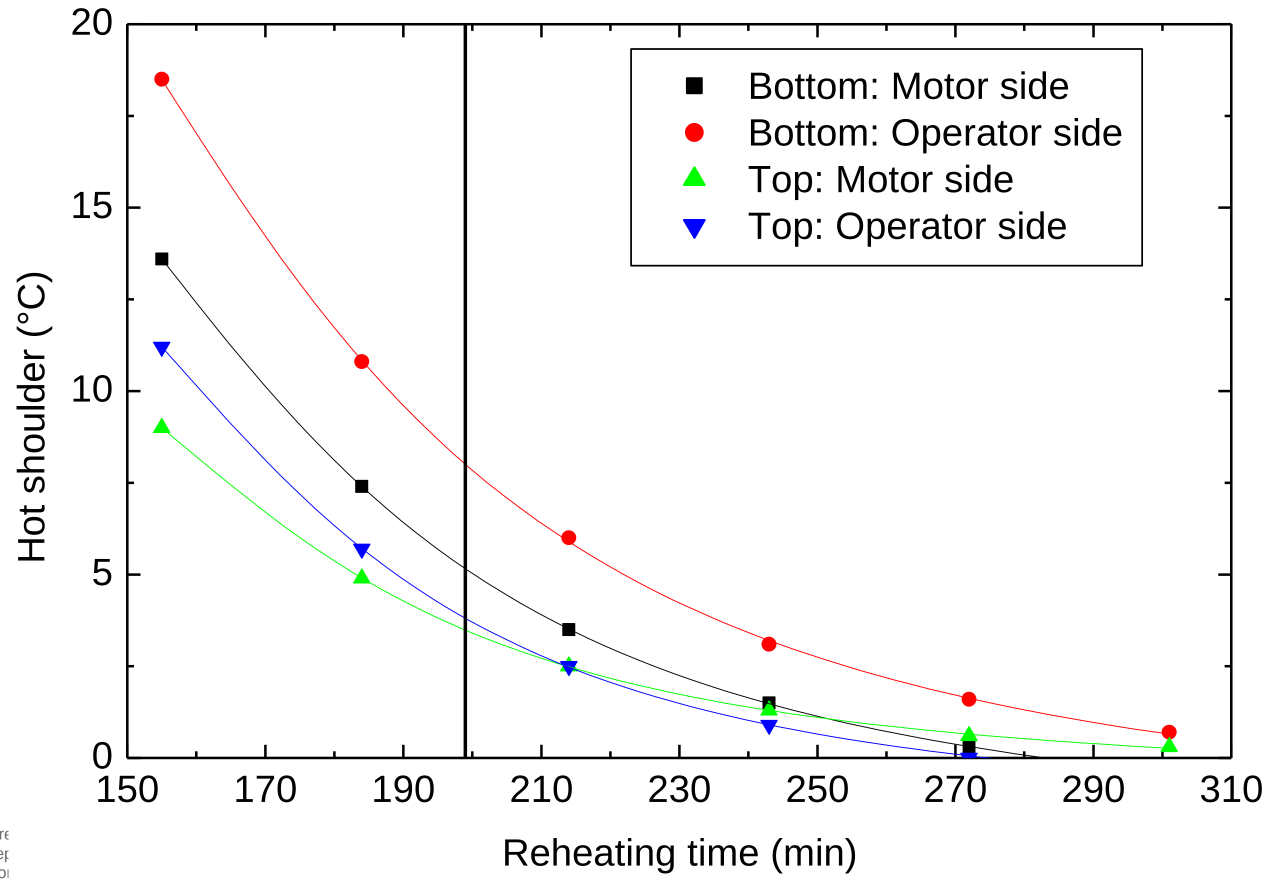
Furnace
Reheating time

- Hot shoulders decrease with increasing reheating time
- 150min to 180min, reduction of 50% of the peak temperature
- A long heating time gives more time for the center of a slab to catch up with the edge temperatures



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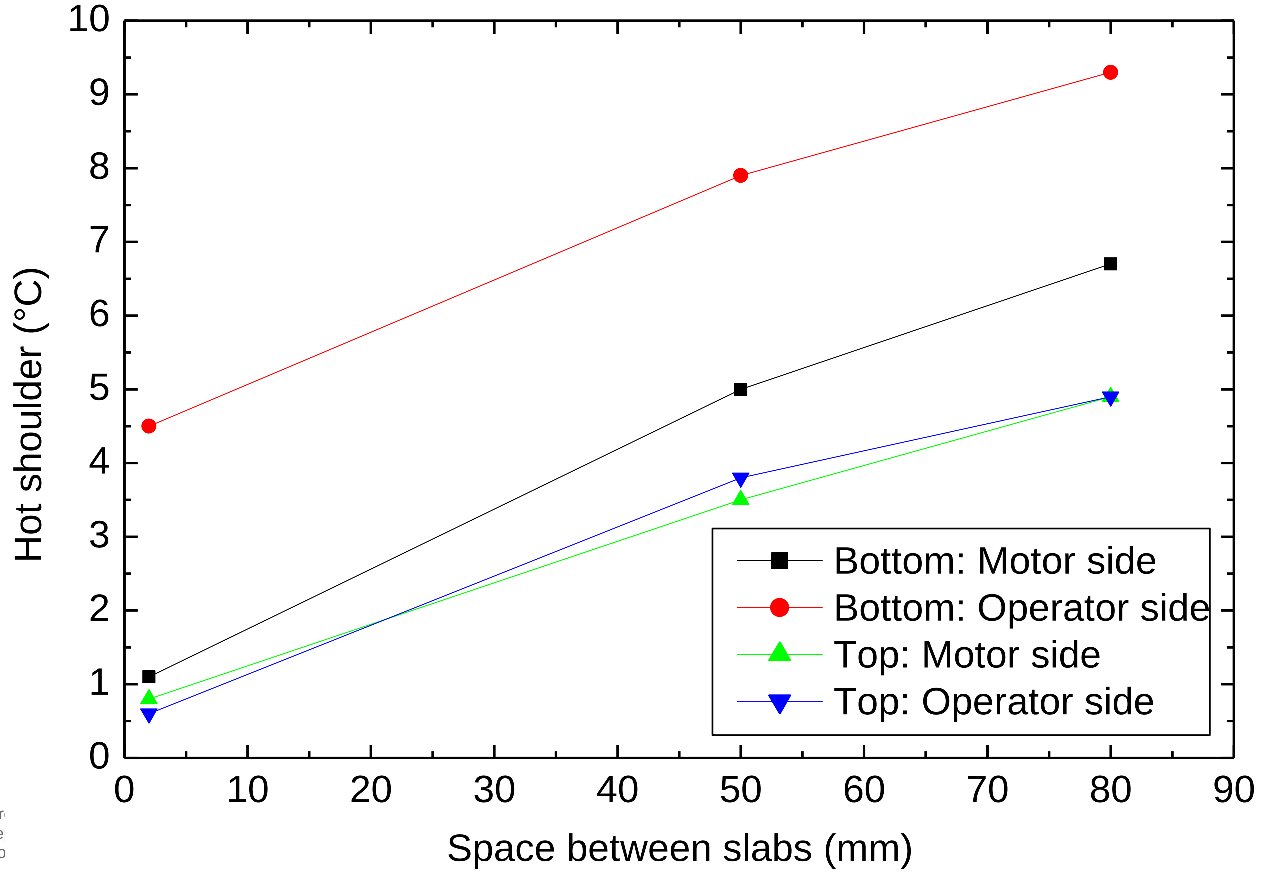
Reheating furnace
Space between slabs

- Space between slabs
  - From 50mm to 2mm, reduction of 70%
  - From 50 to 80mm, increase of 30%
- Edges are more heated because the gas flow can circulated easily



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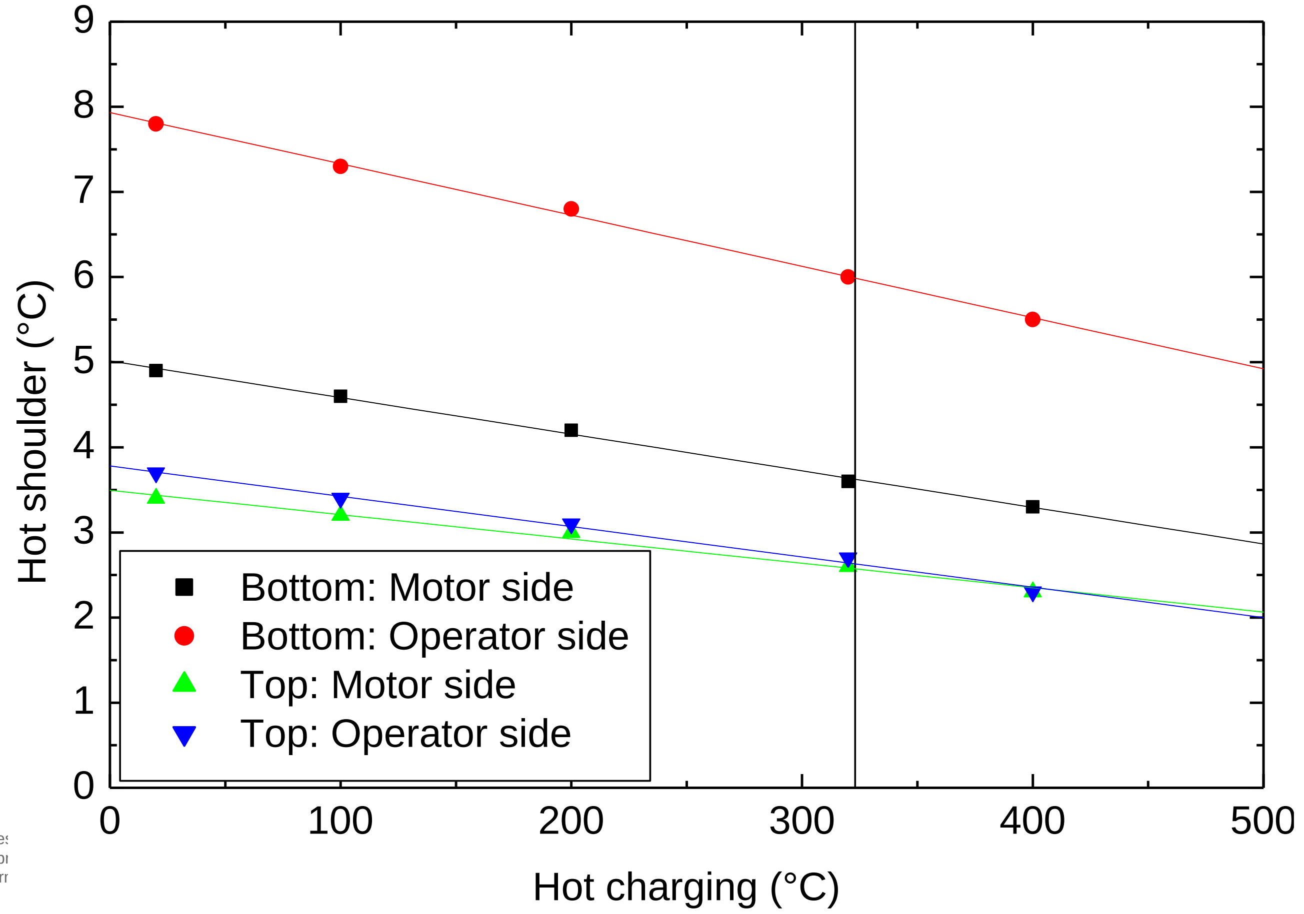
Reheating furnace
Hot charging

- Hot charging (at constant reheating time)
  - 400°C instead of 320°C, reduction of 10% of the peak of temperature
  - Without hot charging instead of 320°C , increase of 34% of the peak of temperature
- At constant reheating time, hot charging gives more time to homogenize the slab temperatures



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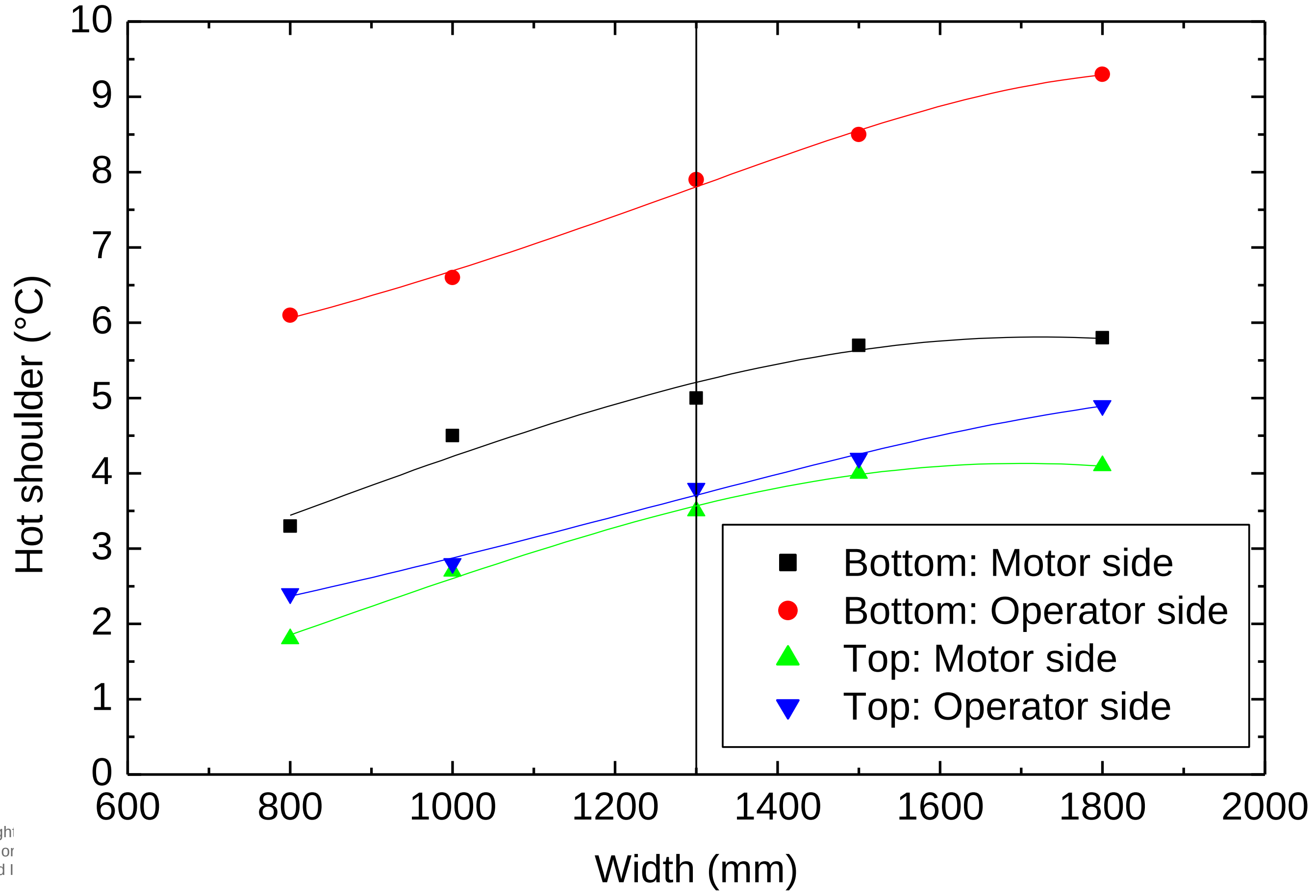
Reheating furnace
Width of the slab

- With constant reheating parameters (reheating time, discharging temperature, slab positions), increasing the slab width from 800 to 1300mm, leads to an increase of the hot shoulders of 35%
- More time is needed to homogenize the temperature of a wider slab



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Reheating furnace
Means to preserve the thermal profile

- Reduction of the space between slabs
- Increase of the reheating time
  - Productivity lowered
- Increase of the reheating time and same productivity
  - Hot charging
  - Early heating (consumption!)
  - Heating zone more powerful
  - New heating strategy
- Loading plan
  - Dimensions and position

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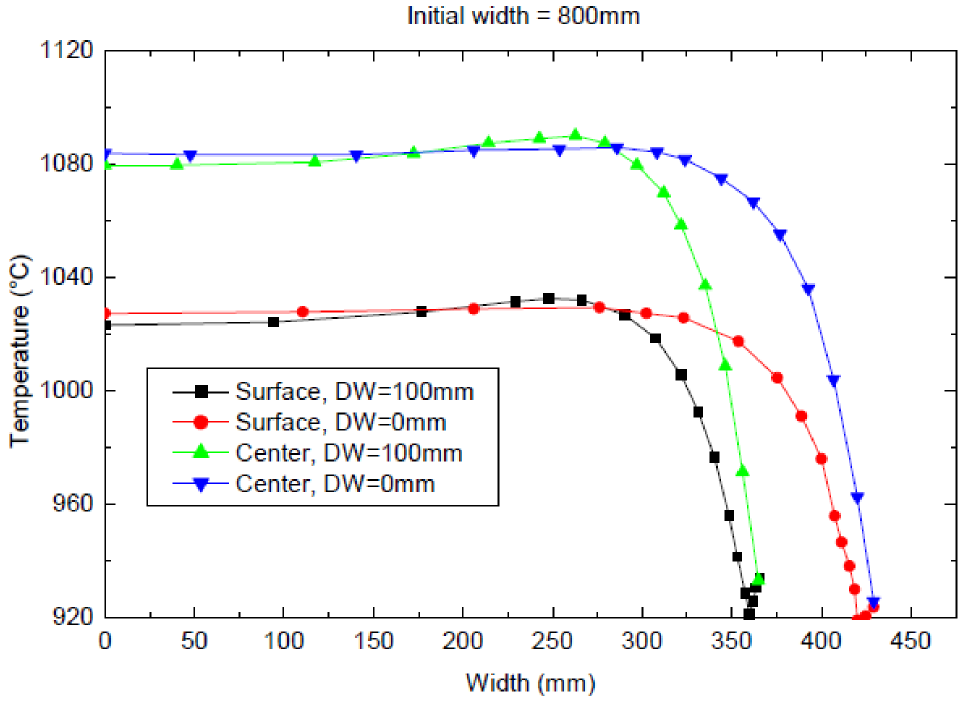
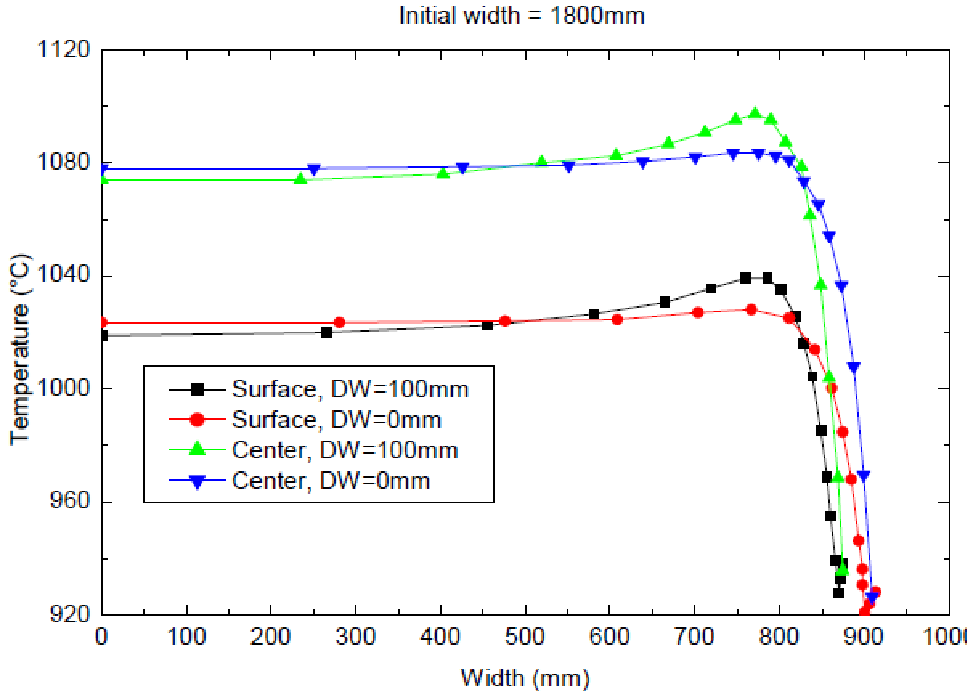
Roughing mill
Width reduction

- FE modeling of the width reduction
  - +4°C for 800mm and a width reduction of 100mm
  - +14°C, for 1800mm and a width reduction 100mm
- The width reduction leads in a dog bone deformation of the slab: during the following horizontal pass more reduction will be applied on these zones, that will receive more energy of deformation and finally a local increase of the temperature is observed
- The model fits well the industrial data: +6 to +18 °C for 100mm width reduction





Roughing mill
Means to preserve the thermal profile

- Width reduction
  - Not really possible, except while avoiding width reduction
  - With a sizing press, the deformation is more homogeneous. Less impact on the hot shoulders is expected

- Rolling direction
  - Covers (active or passive) are an efficient solution to reduce the temperature losses of the tail of the transfer bar by about 10 to 15°C for a passive cover used efficiently

- Transfer bar cooling?
  - Depends on the type of cooling and its use
  - → Water cooling item

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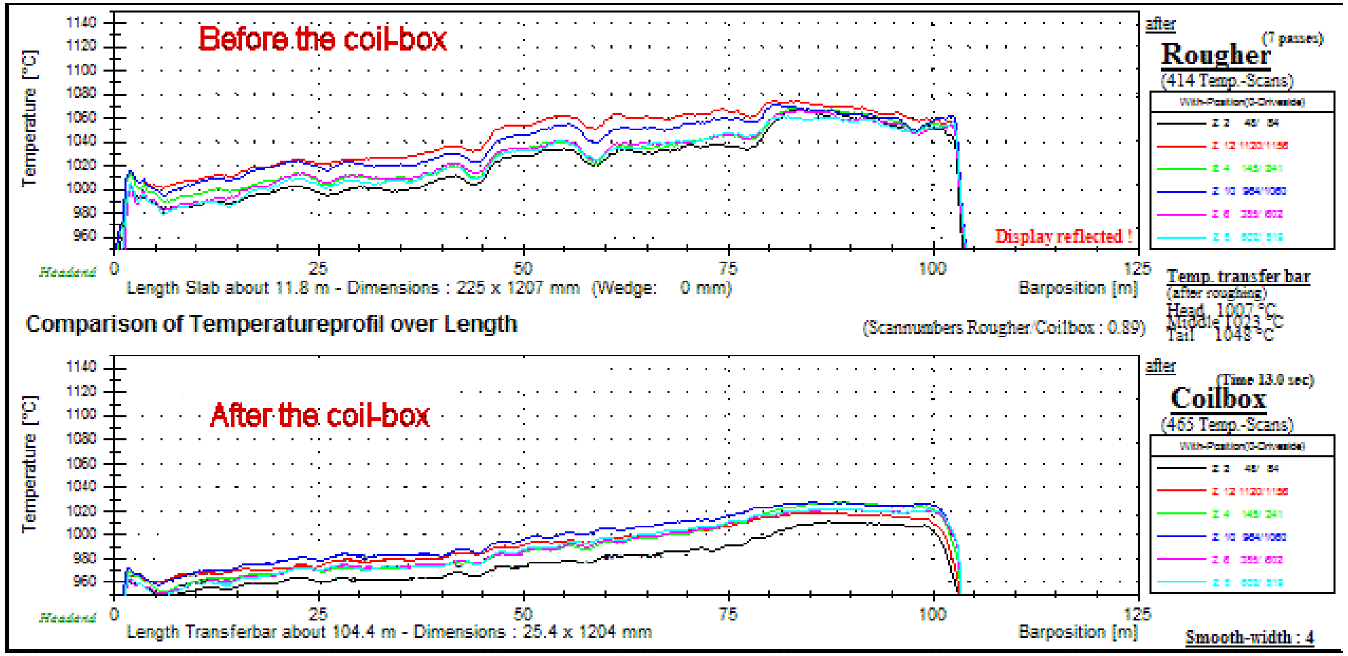
Finishing mill
Coil box

- By inverting the head and tail of a transfer bar, a coil box reduces the thermal difference between head and tail
- It contributes also to decrease of skid-marks
- And if uncoiling takes place quickly, it allows to reduce the hot shoulders. On the other hand, if the uncoiling needs more the transversal profile can be seriously changed



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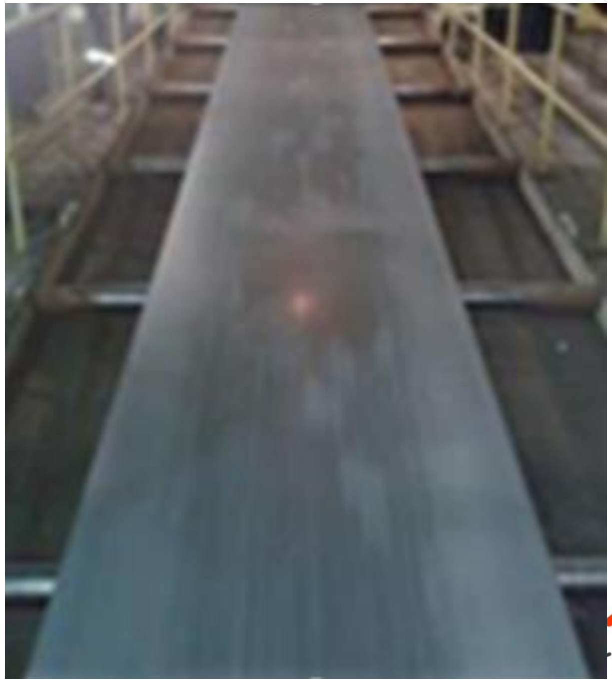
Descaling
As a surface actuator

- Descaling can act on the thermal heterogeneities by 2 ways
  - As a cooling → Cooling
  - As a surface actuator

- If the descaling result is in a non-homogeneous scale thickness or a rough surface or even worst areas that are badly descaled, that will affect directly all water cooling
  - Scale thickness: Scale is an insulating material that will affect the conduction of heat according to its thickness
  - Roughness: a parameter known to act directly on the cooling efficiency while changing the boiling curve
  - Insufficient descaling: scale thickness & roughness + non-well adherent scale that can detach of the strip during cooling
  - Consequences can be much more severe
    - Over-cooling → harder material → final properties that do not meet the specifications → rejections or yield



Finishing mill

- The analysis of large databases of several AM plants does not show a big impact of the finishing mill on the thermal heterogeneities

- Except those resulting of:
  - A bad surface
  - A non-homogeneous cooling

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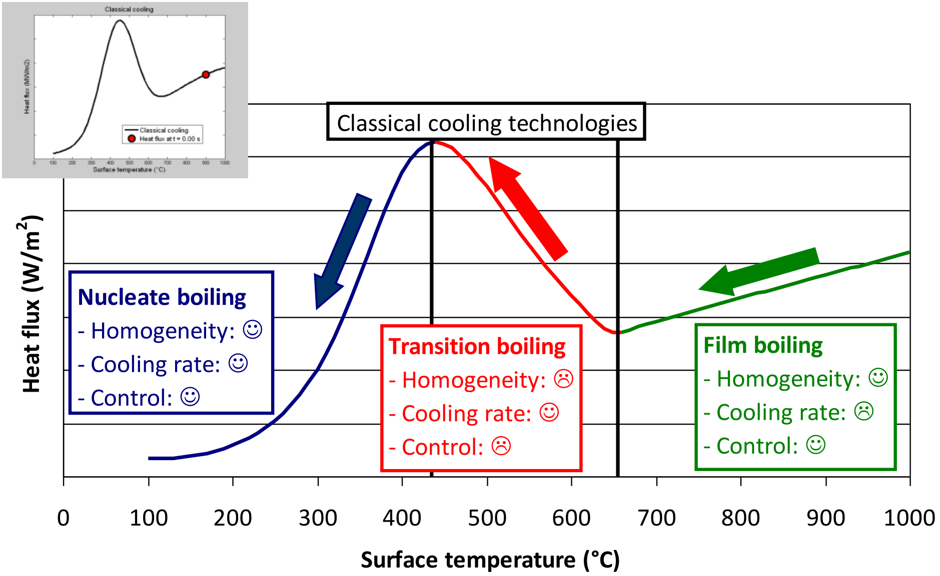
Water cooling
Idealized boiling curve

- The boiling curve of a water cooling device gives the link between the surface temperature of a solid and the heat flux
- In addition to the convective regime (at very low surface temperature), the boiling curve follows 3 boiling regimes:
  - **Film boiling**
  - **Transition boiling**
  - **Nucleate boiling**



- Each boiling regime does not affect a difference of temperature in the same way
  - Film boiling: lower heat flux, for lower surface temperature → a difference of temperature will be reduced
  - Transition boiling: larger heat flux, for lower surface temperature → a difference of temperature will be amplified
  - Nucleate boiling: lower heat flux, for lower surface temperature → a difference of temperature will be reduced

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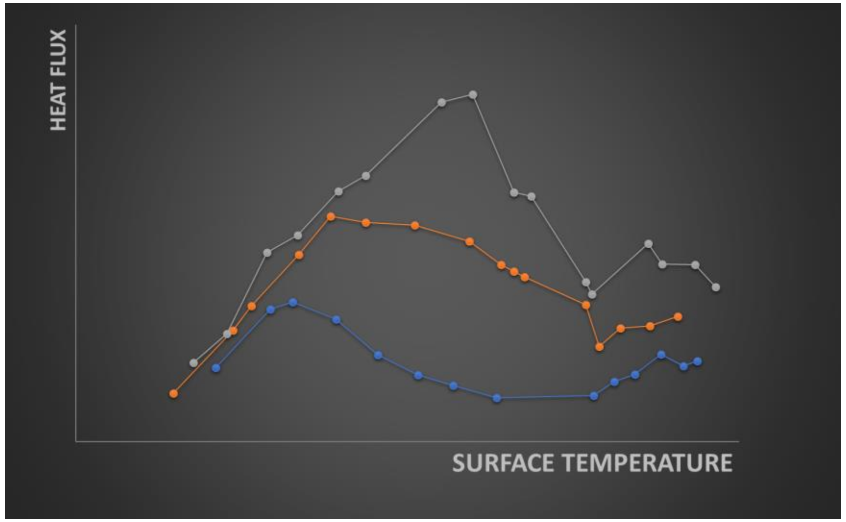
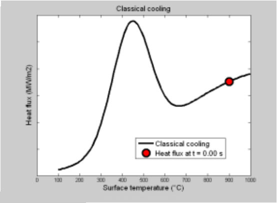
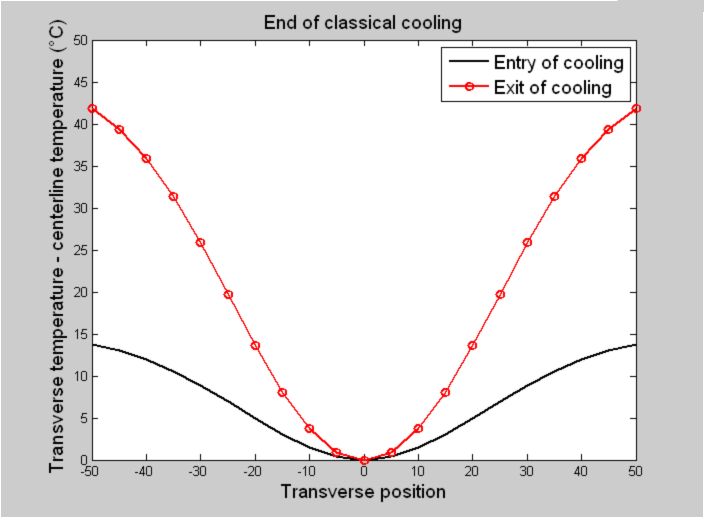
Water cooling
Idealized boiling curve: illustration on the cooling of a strip with hot shoulders

- By knowing the boiling curve it is possible to evaluate the effect of a water cooling device on the thermal homogeneity
- Here we will evaluate the effect of a ROT using a standard cooling technology on the hot shoulders (the same evaluation can be done for the head and tail of a strip, transfer bar and all water cooling: transfer bar cooling, descaling, etc.)
- A symmetrical hot shoulder of 15°C at the exit of the last FM stand is assumed
- Boiling curves: Measured for a ROT equipped with laminar jets







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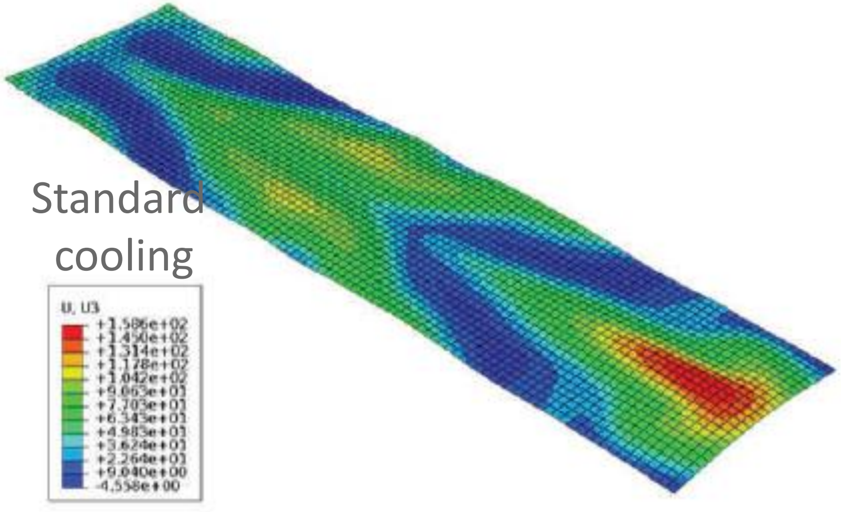
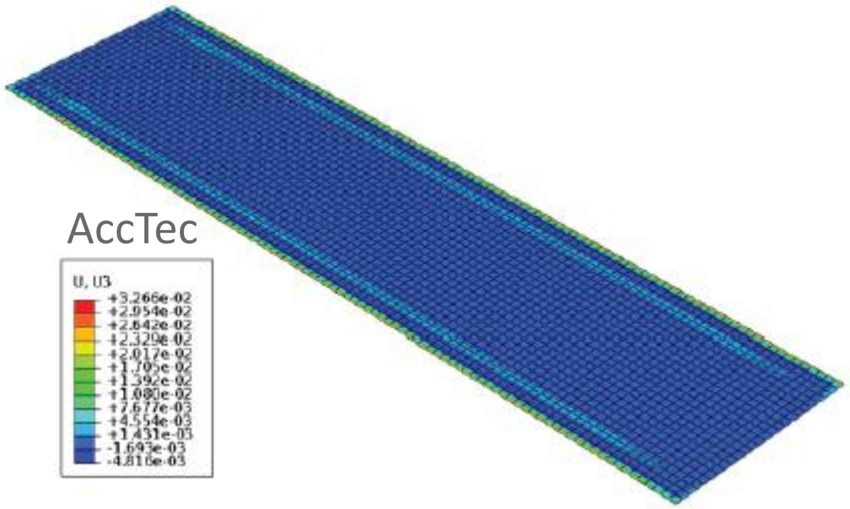
Water cooling
Means to preserve the thermal profile

- Standard cooling technologies are detrimental per nature and will increase the thermal heterogeneities. To reduce the bad effect of these technologies, additional controls have to be used: thermal crown, edge masking, variable valves, etc.
- More suitable cooling technologies are known to improve the thermal profile and gives much better results in terms of flatness and homogeneity of the mechanical properties (Super-Olac-H, ACCtec)

Flatness results





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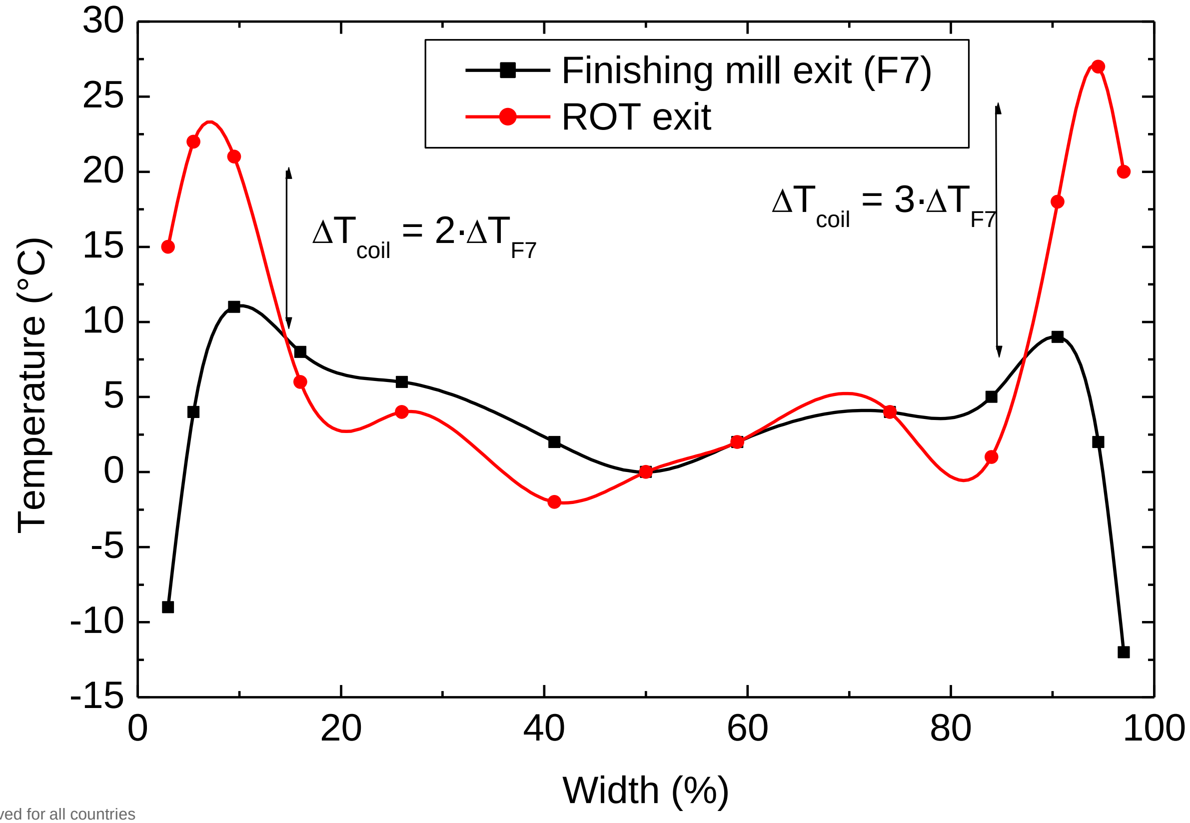
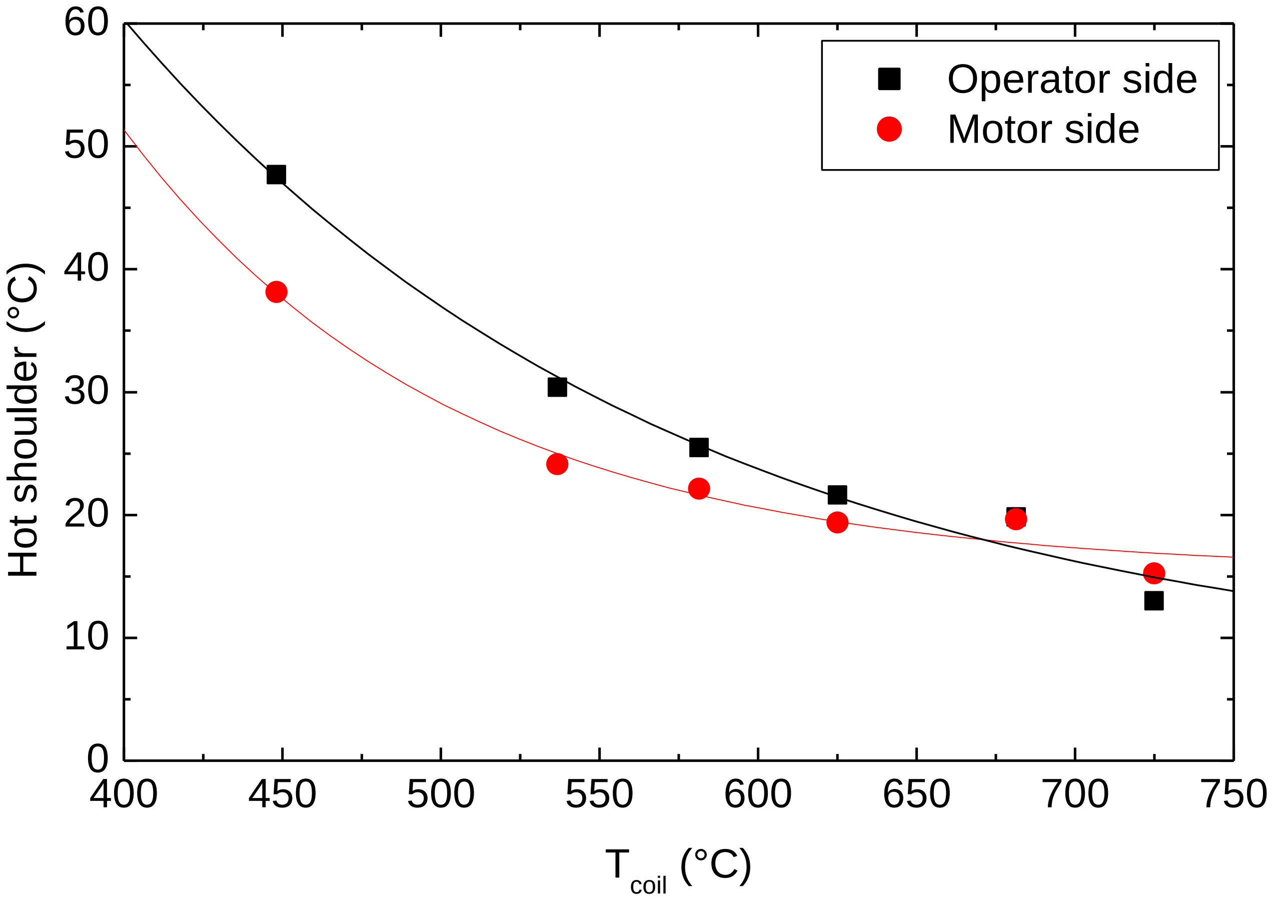
Run-Out-Table

- Deteriorate the thermal profile while amplify the hot shoulder until a factor 3
- Main parameters:
  - Coiling temperature
  - Thickness



ROT
Coiling temperature

- Hot shoulders increase with colder coiling temperatures with an amplification of the hot shoulders until a factor 3
- Directly related to the amount of water used and because for the coldest surface temperature, the strip is mainly cooled also in the transition boiling regime



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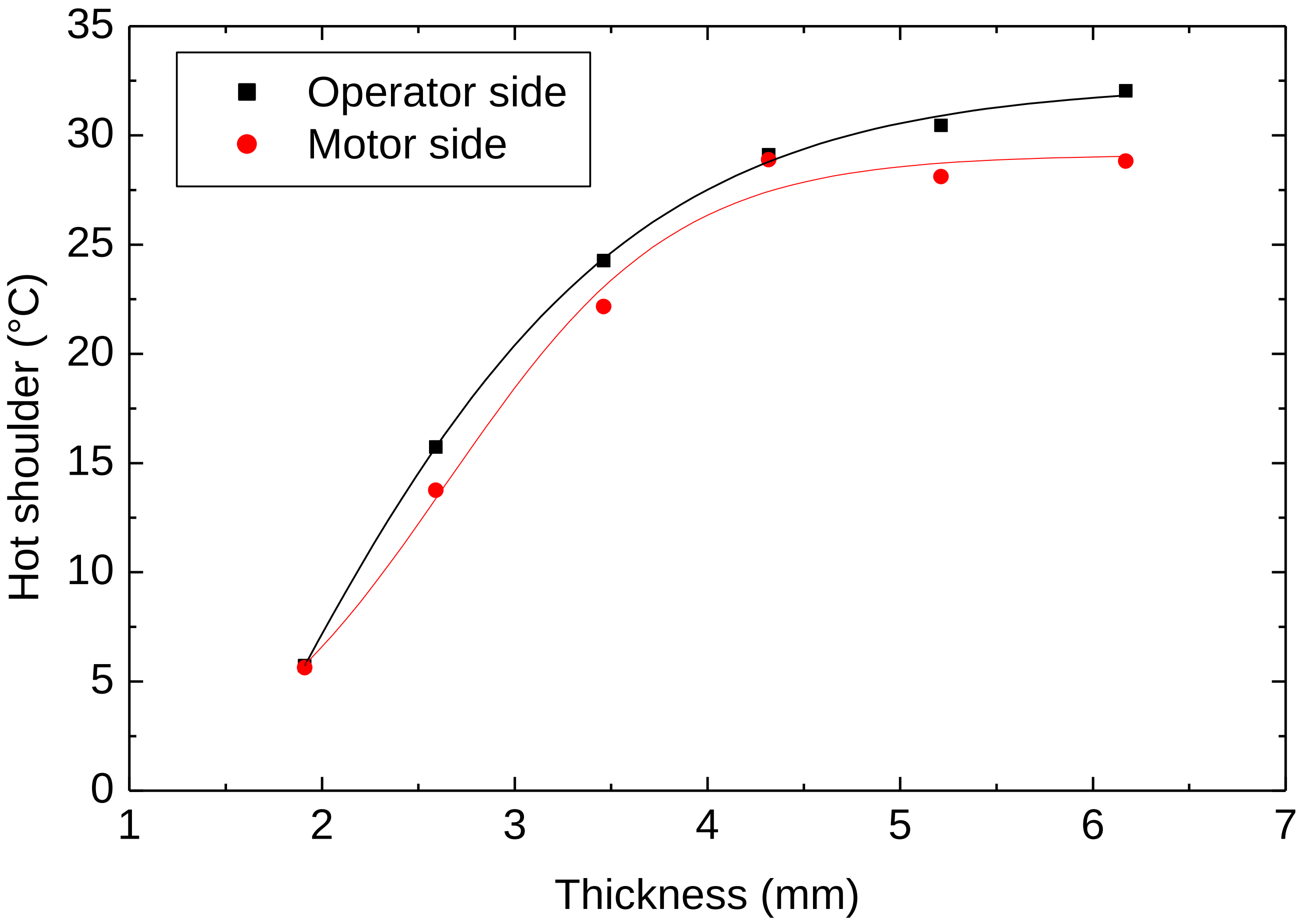
ROT
Thickness

- Hot shoulders increase with the thickness
- Directly related to the amount of water used and to the surface temperature reached during cooling (≠ of the coiling temperature)



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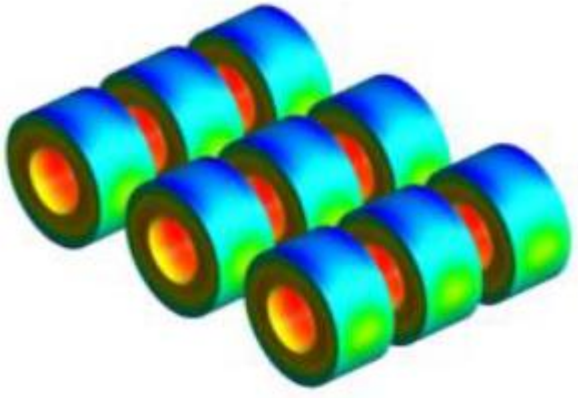
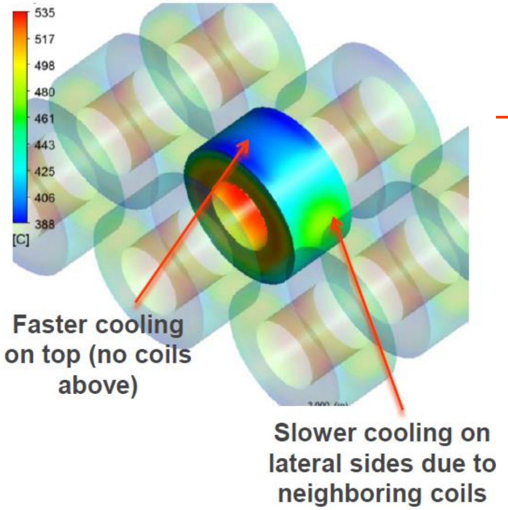
ROT
Means to preserve the thermal profile

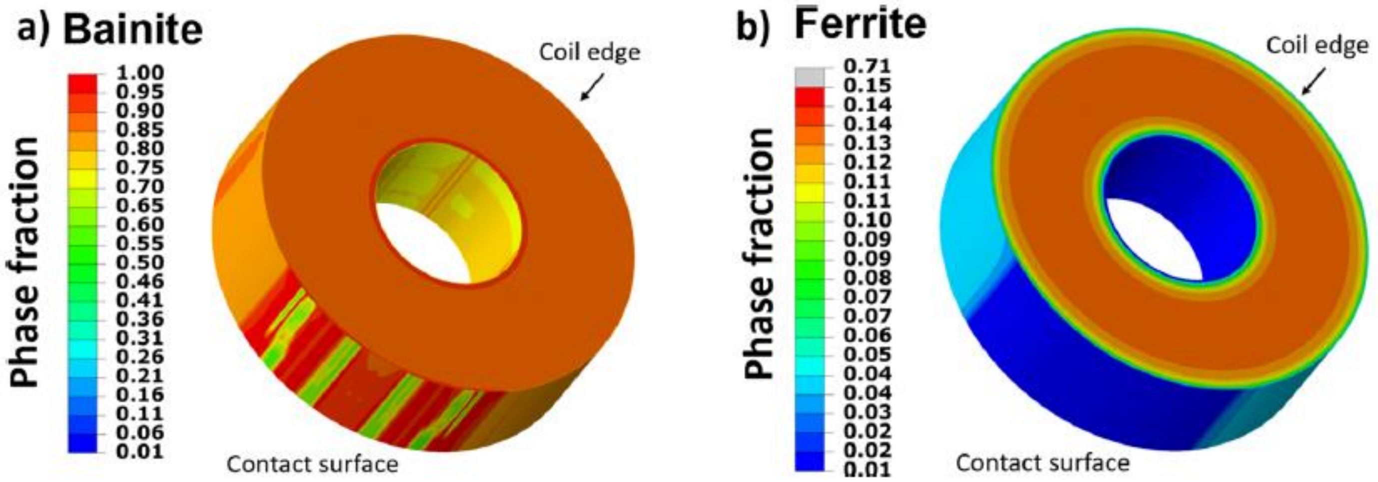
- No clear means to preserve the thermal profile, because we cannot act on the:
  - Coiling temperature
  - The thickness
  - The width
- Actions has to be taken before the Run-Out Table to limit as much as possible the difference of temperature
- Rewetting with sprays can occur at higher temperature compared to impinging jets, if properly chosen it could help in reducing the amplification of the thermal heterogeneities

Coil cooling





- Coil cooling is heterogeneous (head vs tail, edges)
  - Dimensions, shape of the coil, wraps
  - Unsymmetrical cooling conditions
  - Not homogeneous temperatures at the exit of the ROT
  - Not homogeneous phase fraction at the exit of the ROT
- As a consequence, the phase transformation is not homogeneous, nor the final mechanical properties of sensitive grades
- After uncoiling, strips can also exhibit a bad flatness requiring repairs



J. Ilmola et al., “Coupled heat transfer and phase transformations of dual-phase steel in coil cooling,” Materials Today Communications, vol. 26, p. 101973, Mar. 2021, doi: 10.1016/j.mtcomm.2020.101973.

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Coil cooling
Means to preserve the thermal profile

- Homogeneity at the entry of the coiler as to be as good as possible
- Then to limit the effect of the various cooling conditions around the coils, solutions will depend on the grade
- Very sensitive grades may require a controlled cooling with covers

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Conclusions

- The furnace is at the origin of the thermal heterogeneities, even if continuous casting has to be also taken into account

- Several HSM tools act on the thermal profile directly while acting on the temperature (width reduction, water cooling, descaling, coil cooling) or indirectly while acting on the surface (descaling)

- The contribution can be summarized as:

  - Width reduction: creation and amplification of transversal heterogeneities
  - Water cooling: reduction and amplification of all temperature differences (head/tail, top/bottom, motor/operator sides)
  - Descaling: creation of temperature differences mainly aligned
  - Coil cooling: creation and amplification

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