Effect of Ti microalloying and residual S content on the hot ductility of a boron steel

Montaña, Y[1,2]; Arruabarrena, J[1,2]

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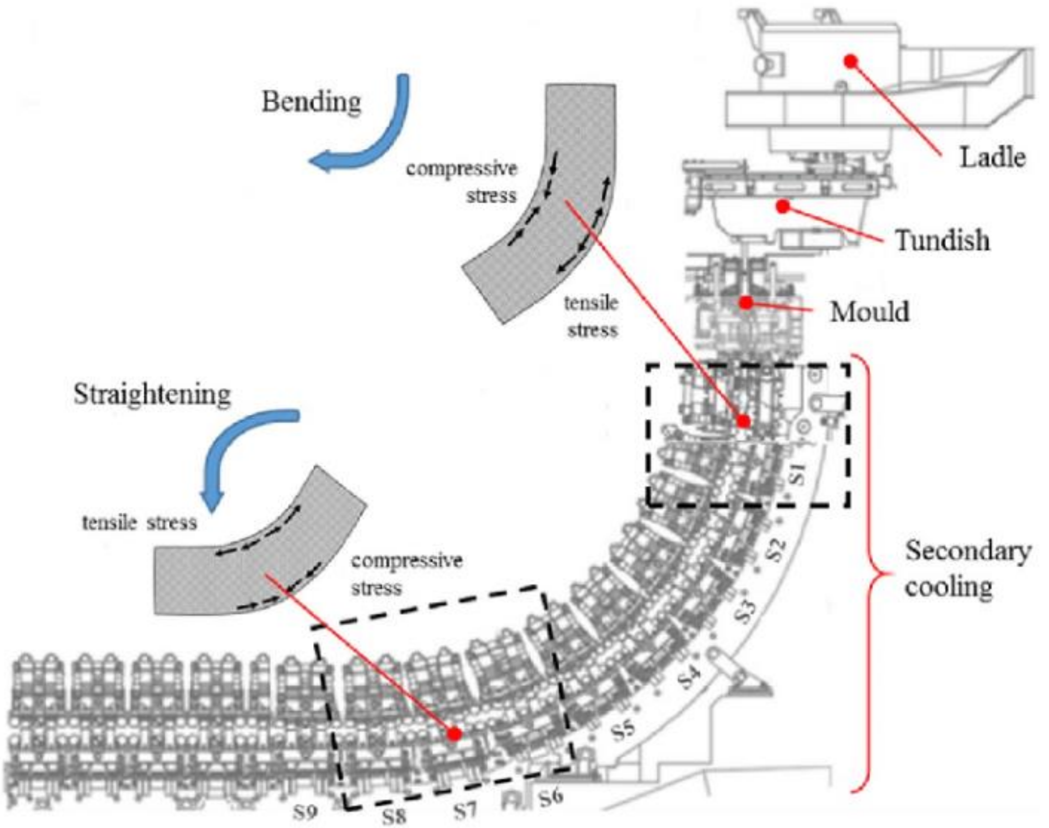
Introduction

Continuous Casting process



[1]Rosa M. Pineda Huitron, Pavel E. Ramirez Lopez, Esa Vuorinen, Robin Jentner, Maija E. Karkkainen. *Materials Science & Engineering A*, 772 (2020) 138691.

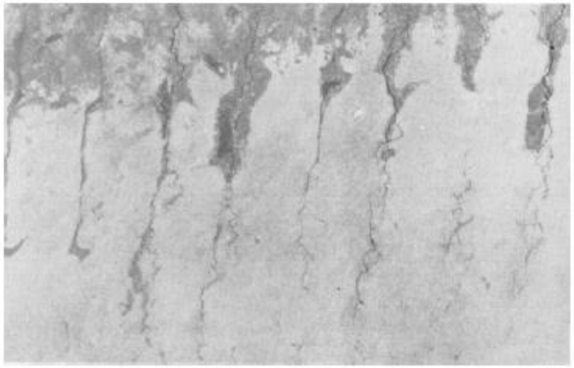
Introduction

Continuous Casting process

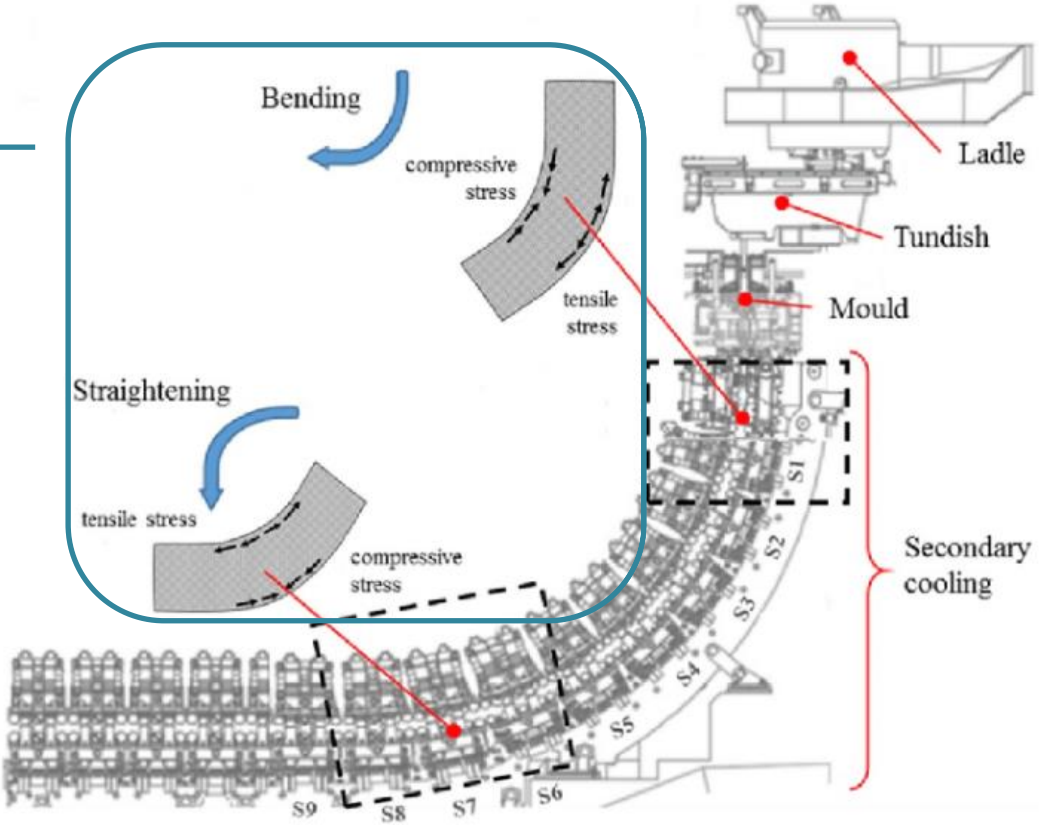
Bending and straightening process

- ε = 1-2%
- $\varepsilon' = 10^{-3} - 10^{-4}\ s^{-1}$
- T range = 1000ºC - 700ºC

Ductility loss → surface cracking



[2]J. K. Brimacombe and K. Sorimachi. *Metallurgical Transactions B* Volume 8B, 1977 – 489



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Introduction

Continuous Casting process

<u>Bending and straightening process</u>

- ε =1-2%
- $\varepsilon' = 10^{-3}$ -10^{-4} s^{-1}
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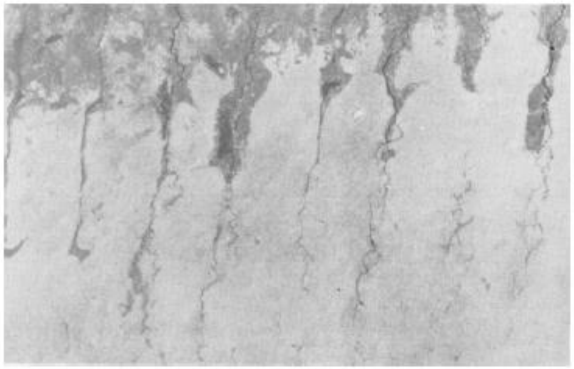
<u>Ductility loss → surface cracking</u>



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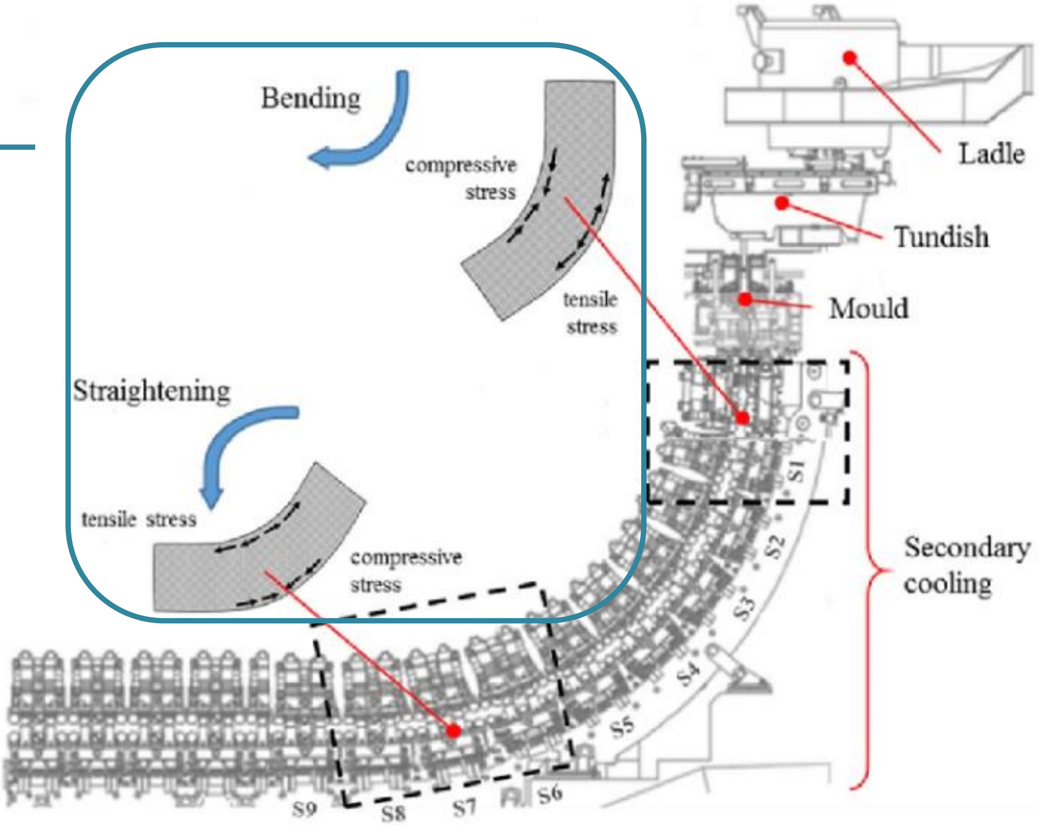

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<u>Factors</u>

- Composition → microalloyed steels!!
- Microstructure (grain size and precipitation)
- Process variables (thermal cycle and casting speed)

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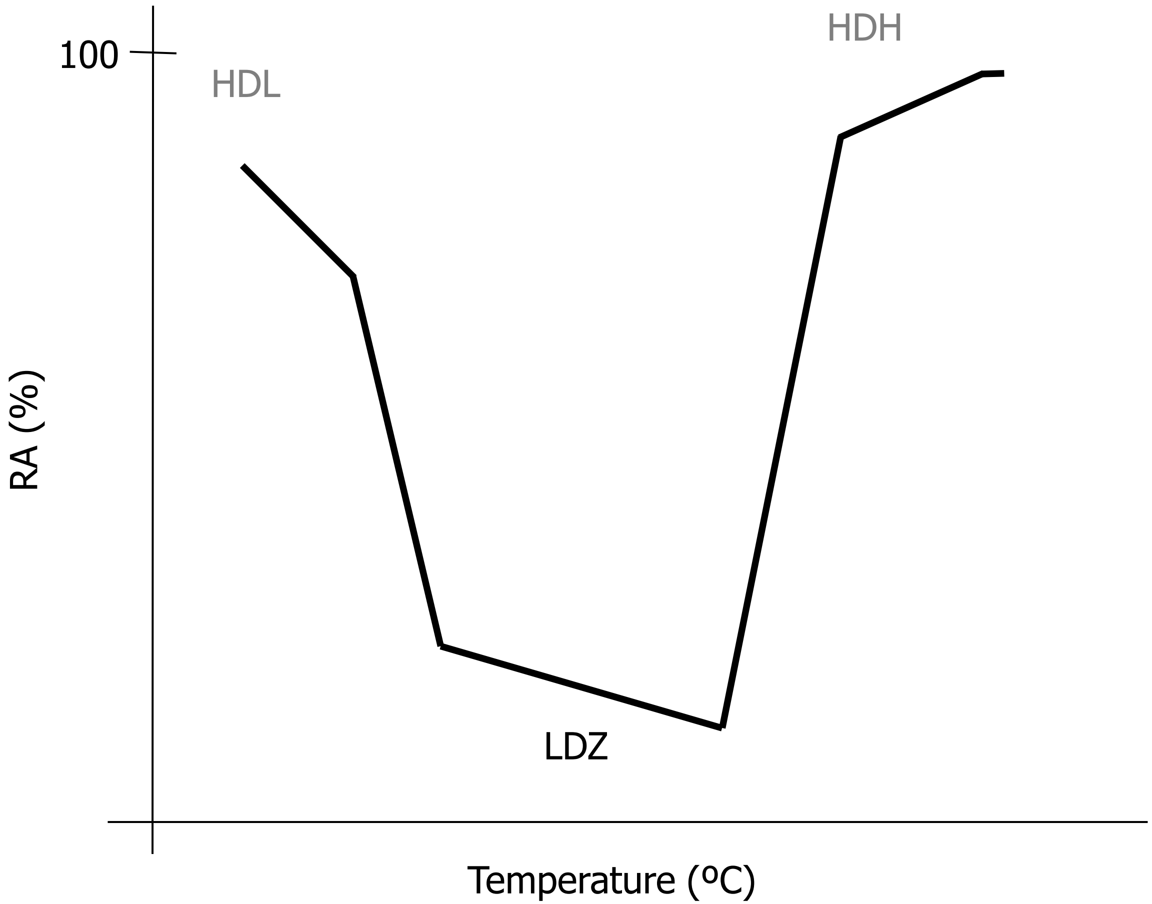
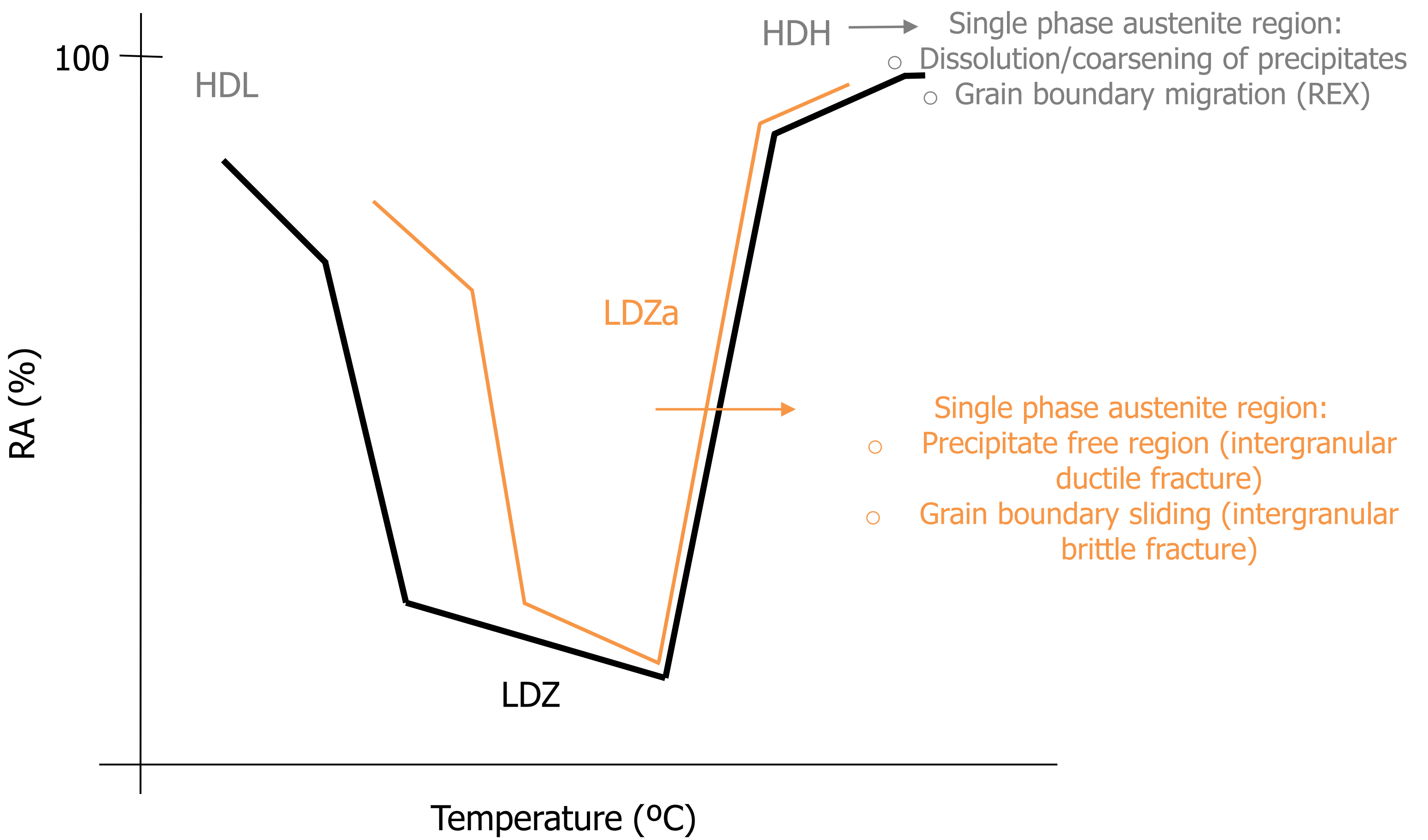
Ductility trough



Hot tensile tests

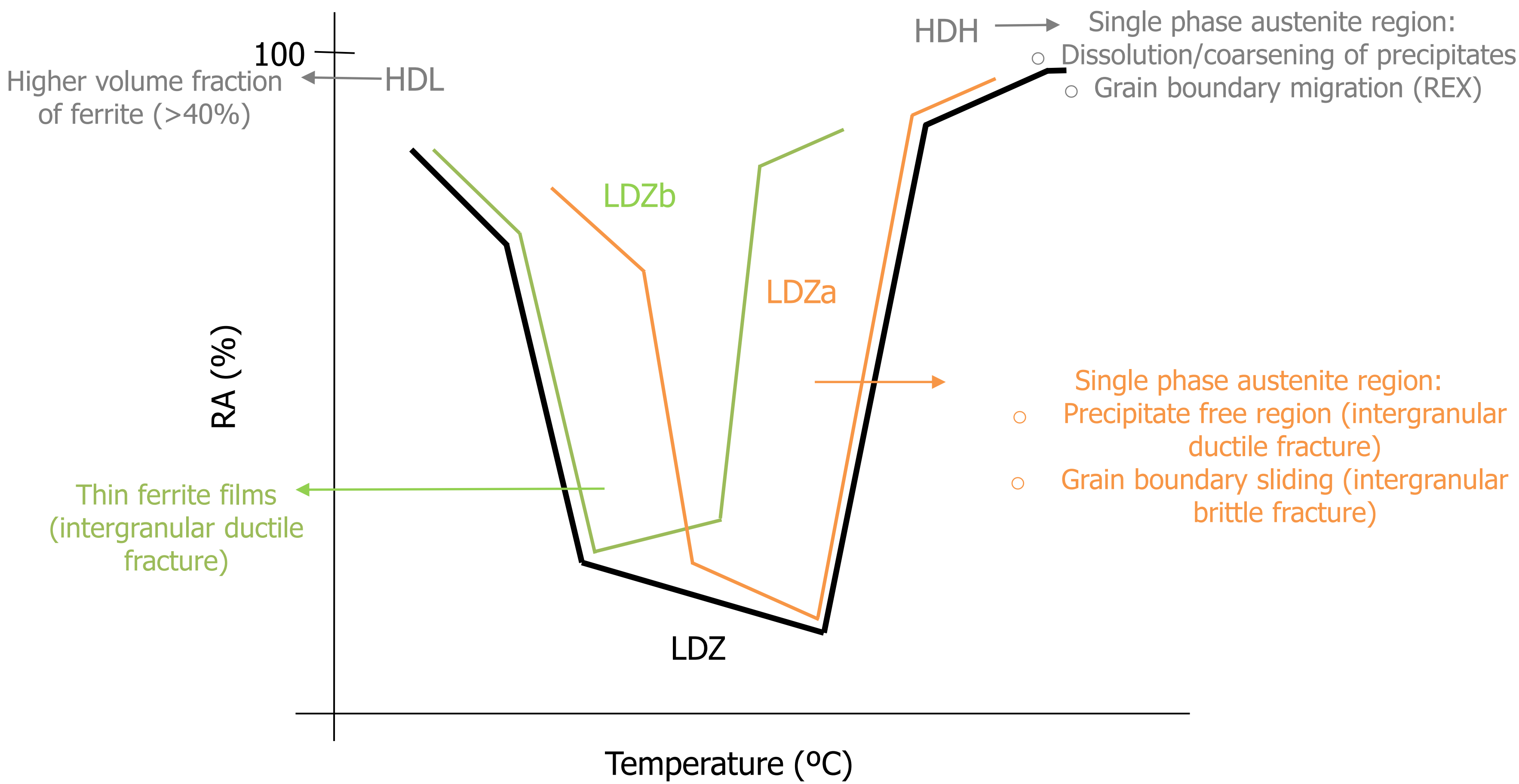
Introduction

Ductility trough



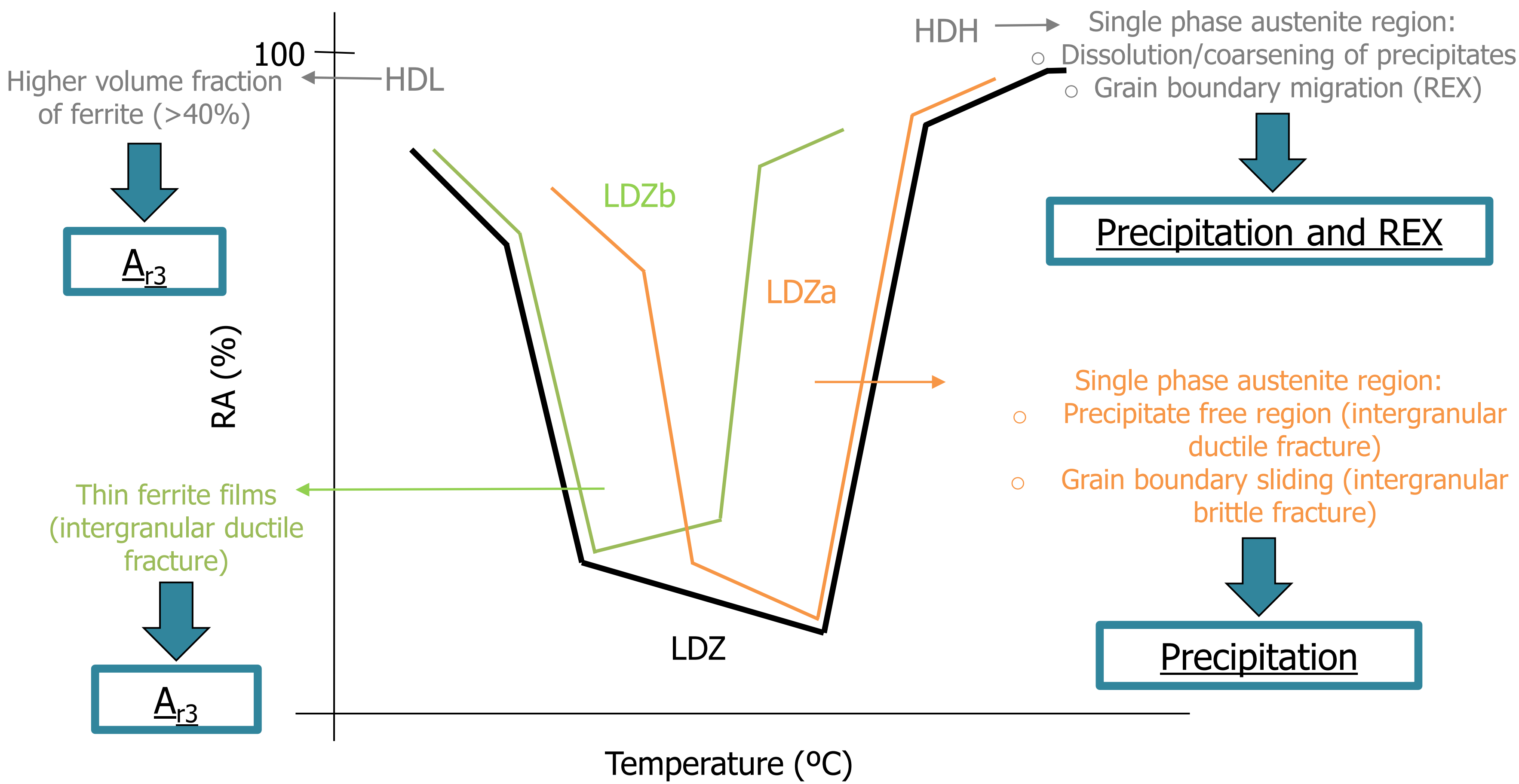
Hot tensile tests

Ductility trough



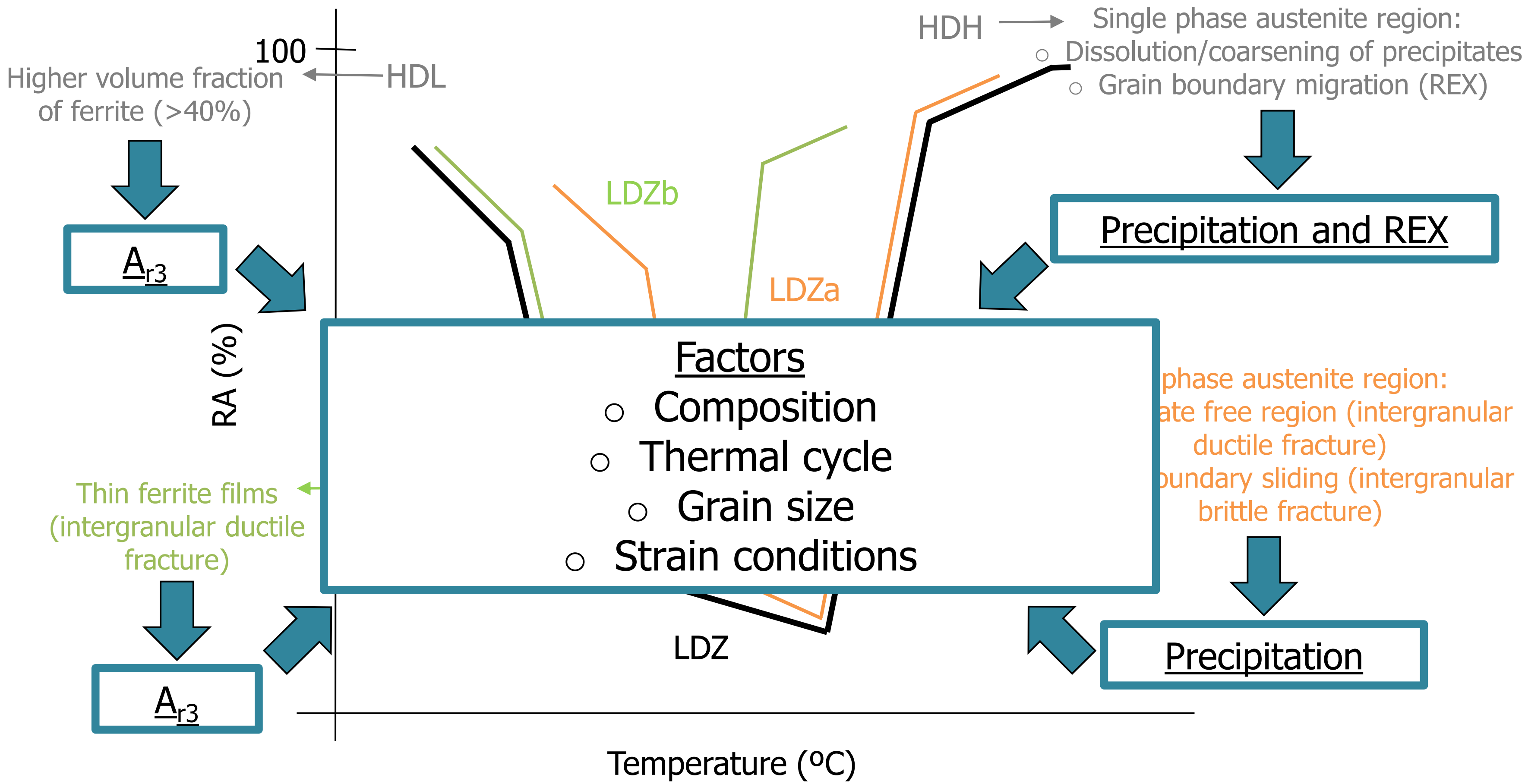
Hot tensile tests

Ductility trough



Hot tensile tests

Ductility trough



Hot tensile tests

Steel compositions

Composition in wt%

	C	Si	Mn	P	S	Cr	Mo	Al	N	Nb	V	Cu	B	Ti
BC	0.15	0.3	1.42	0.012	0.002	0.02	0.003	0.037	0.007	0.033	0.011	0.012	0.0000	0.000
BC-B	0.15	0.3	1.42	0.012	0.002	0.02	0.003	0.037	0.007	0.033	0.011	0.012	0.0025	0.000
BC-BTi150	0.15	0.3	1.42	0.012	0.002	0.02	0.003	0.037	0.007	0.033	0.011	0.012	0.0025	0.015
BC-BTi300	0.15	0.3	1.42	0.012	0.002	0.02	0.003	0.037	0.007	0.033	0.011	0.012	0.0025	0.030
BC-BTi600	0.15	0.3	1.42	0.012	0.002	0.02	0.003	0.037	0.007	0.033	0.011	0.012	0.0025	0.060

***BC (Base Composition)**

Ingots processed by remelting a base composition and the addition of B and Ti.

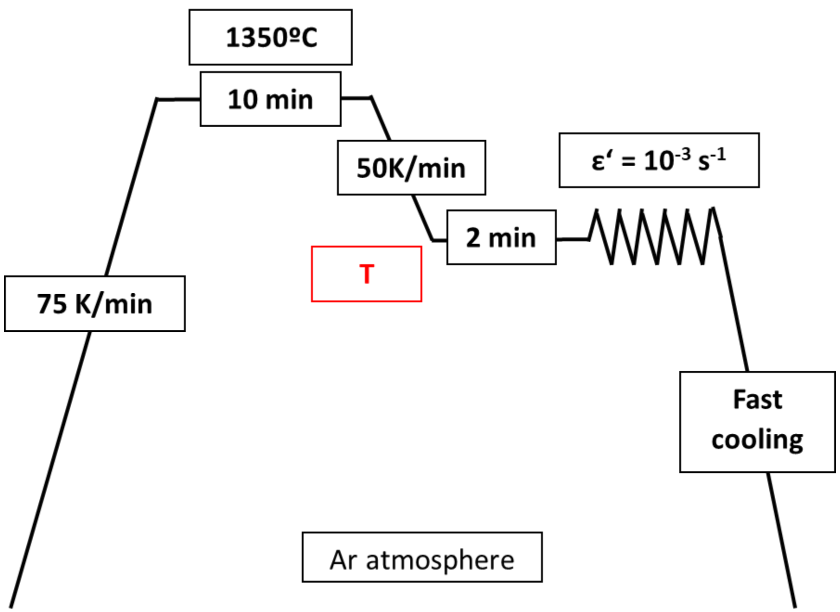
B conditioning and expected precipitation (based on THERMODYNAMIC EQUILIBRIUM (Thermo-Calc TCFE9))

$Ti/N_{stoic} = 3{,}417$

		TiN	MnS	NbC	BN	AlN	B in ss (or Fe23(C,B)6)
	BC	✗	✓	✓	✗	✓	✗
	BC-B	✗	✓	✓	✓	✓	✓
Hypo-stoichiometric Ti/N →	BC-BTi150	✓	✓	✓	✓	✓	✓✓
Stoichiometric Ti/N →	BC-BTi300	✓	✓	✓	✗	✗	✓✓✓
Hyper-stoichiometric Ti/N →	BC-BTi600	✓	✓	✓	✗	✗	✓✓✓

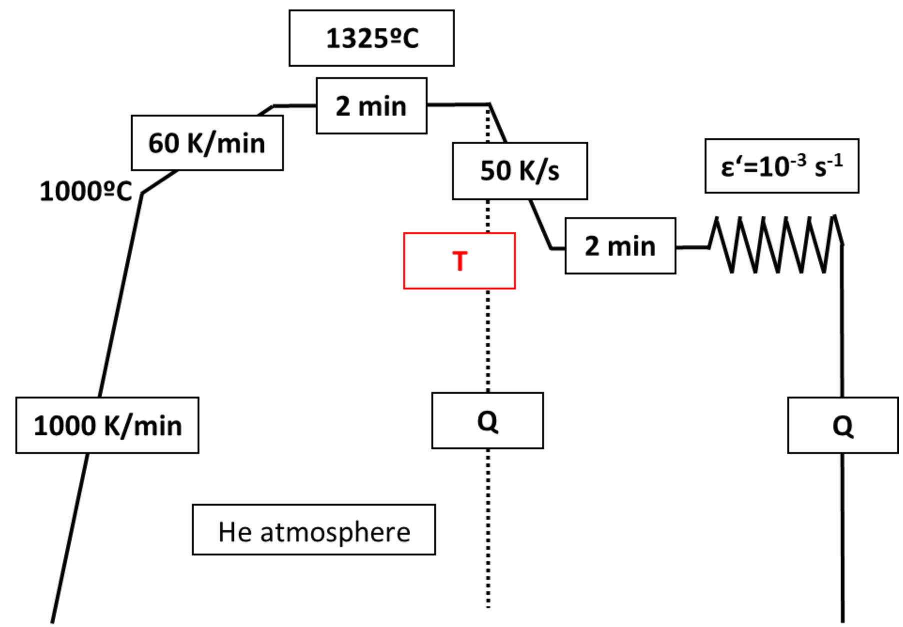
Experimental techniques

Hot tensile tests



- Reduction in area

Dilatometry tests

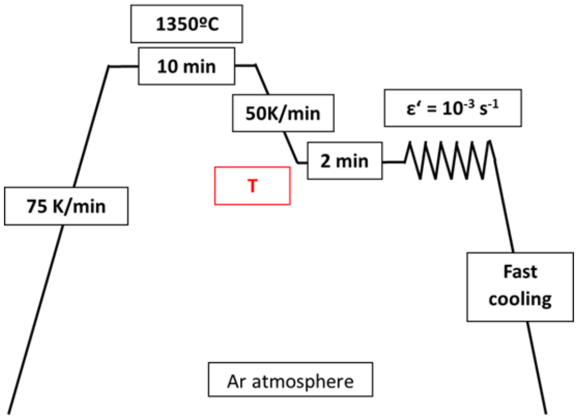


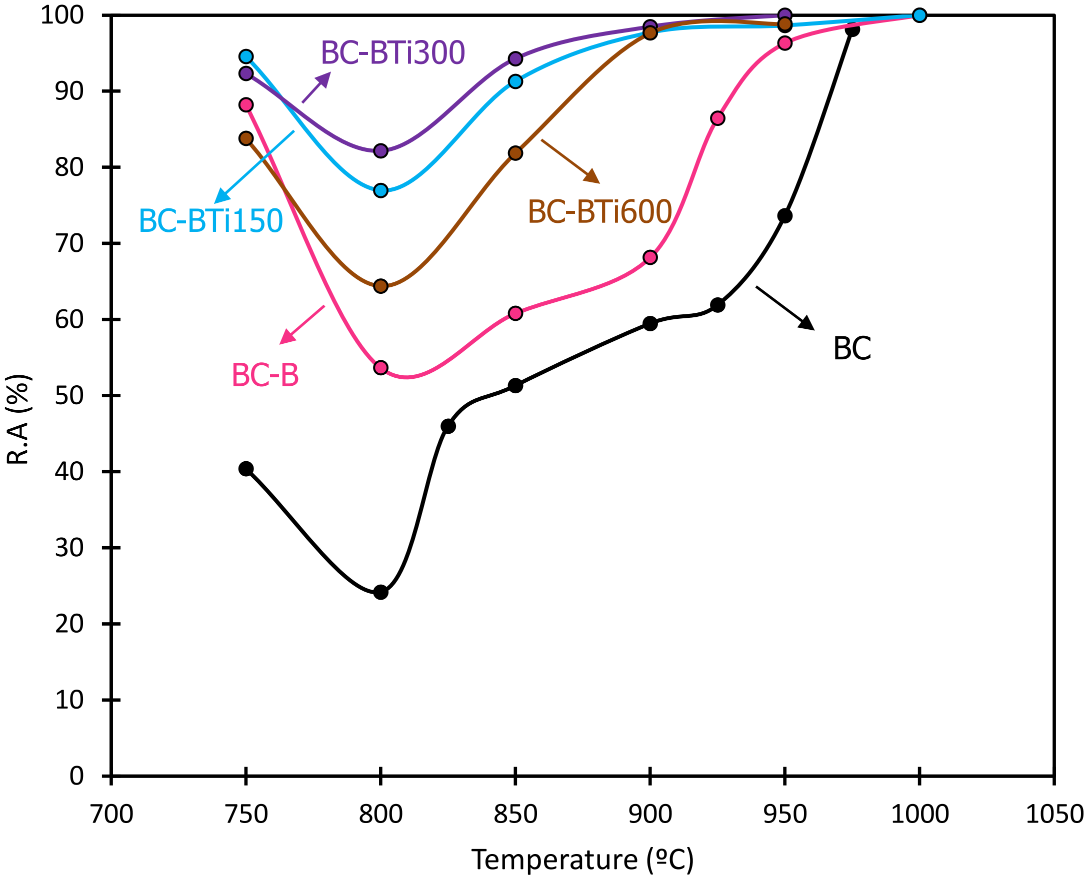
- A_{r3} (OM)
- Precipitation evolution (FEG-SEM and EDS)

Results and discussion

Characterization of the ductility trough

Hot tensile tests





Main conclusions:

- BC steel starts ductility loss at 950ºC and it extends until 800ºC. At 750ºC ductility starts to recover

- B addition (25 ppm) improves hot ductility shifting the high temperature low ductility zone to lower temperatures (around 50ºC)

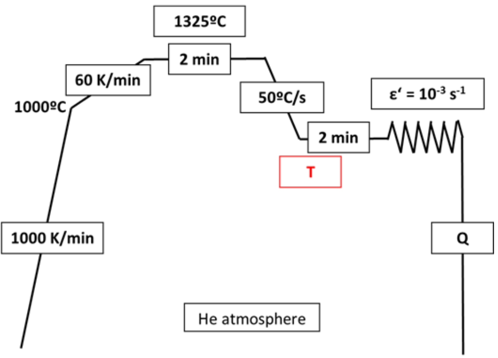
- When B is protected by Ti, the ductility trough notably reduces and the ductility drop occurs smoothly as the temperature decreases

- The optimal result is achieved when Ti is added in the stoichiometric range. When Ti is in the hypo / hyperstoichiometric ranges ductility trough tends to increase.

Results and discussion

Characterization of A_{r3}

Dilatometry tests

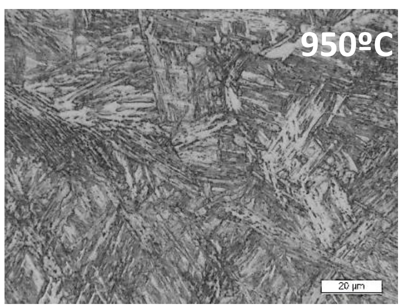
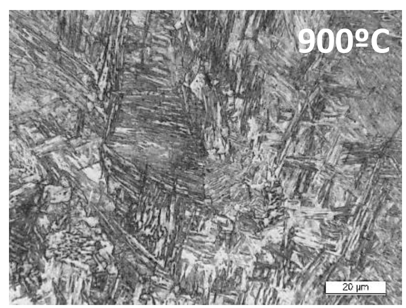
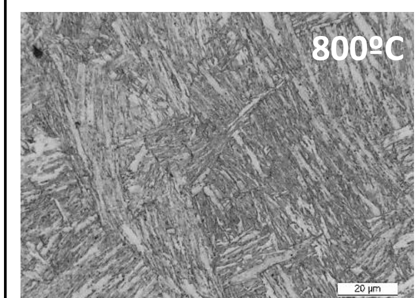
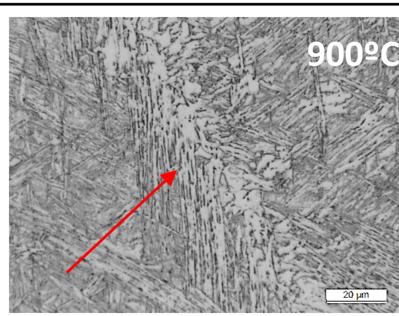
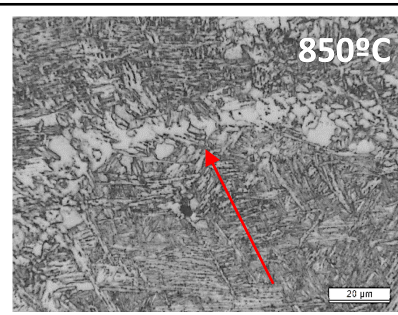


Main conclusions:

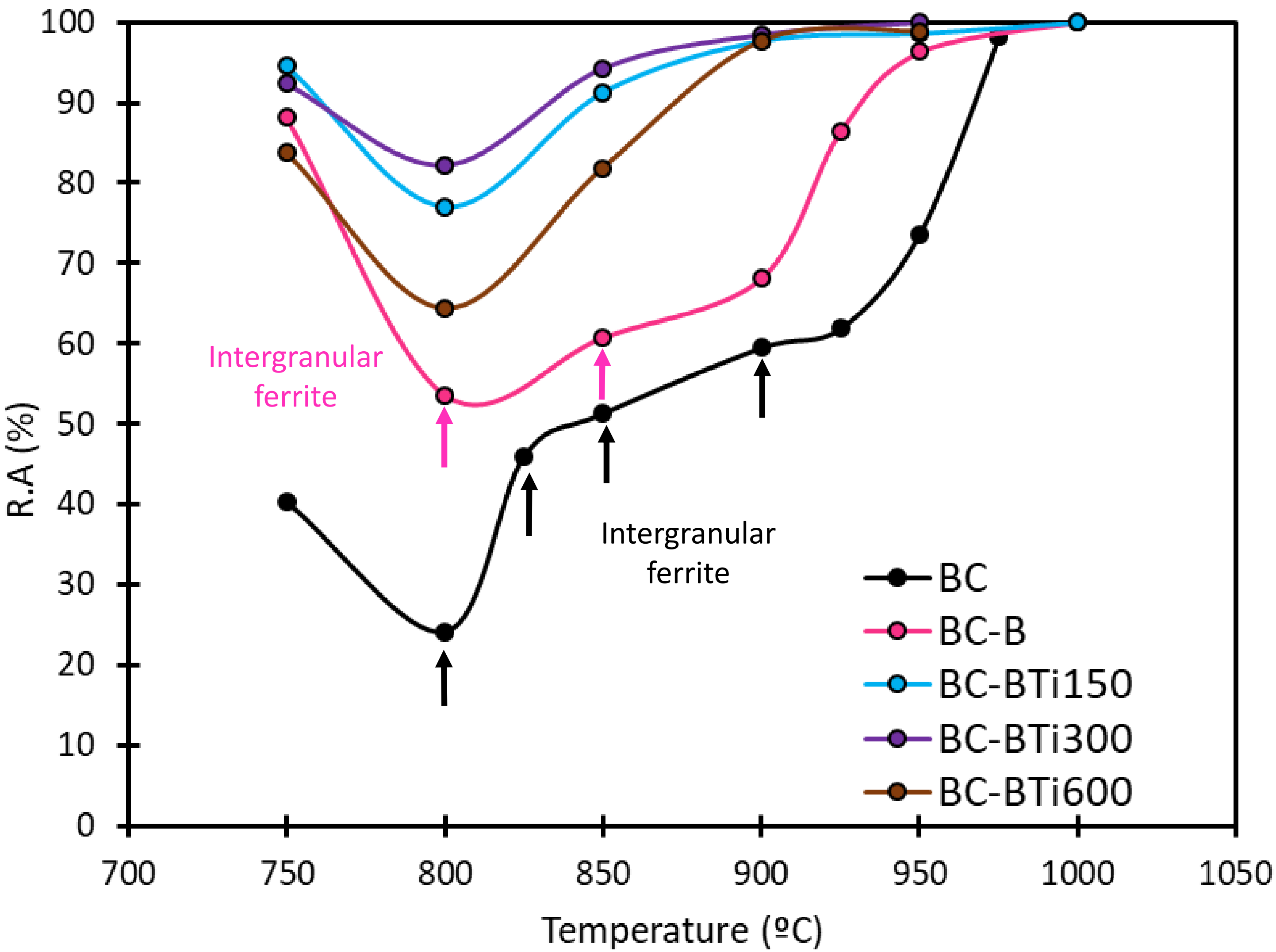
- BC steel shows intergranular ferrite at 900ºC → deformation induced transformation
- BC-B delay ferrite transformation to 850ºC → hardenability effect of B
- BC-BTi300 does not show ferrite even at 800ºC → increase of B in ss implies increasing of hardenability

Cooling rate = 0,83 ºC/s

A_3=820ºC (thermodynamic equilibrium (Thermo -Calc TCFE9))

	BC	BC-B	BC-BTi300
NO ferrite in AGB			
Ferrite in AGB			

Characterization of A_{r3}



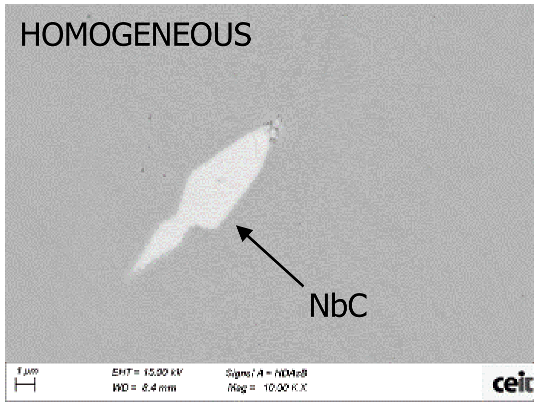
Results and discussion

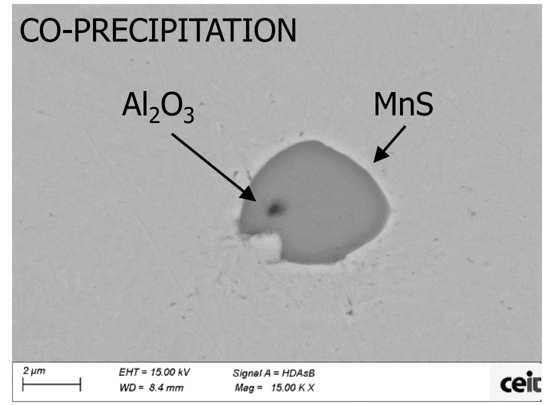
Characterization of precipitation

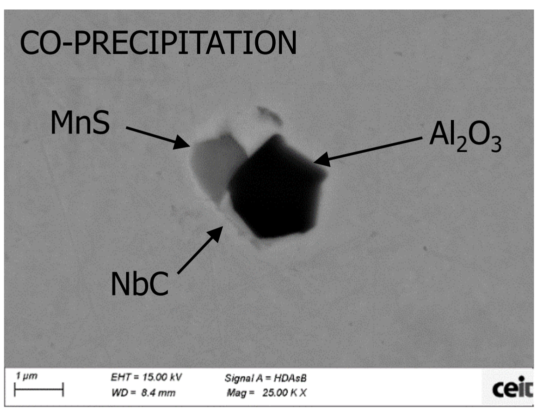
T= 1325ºC

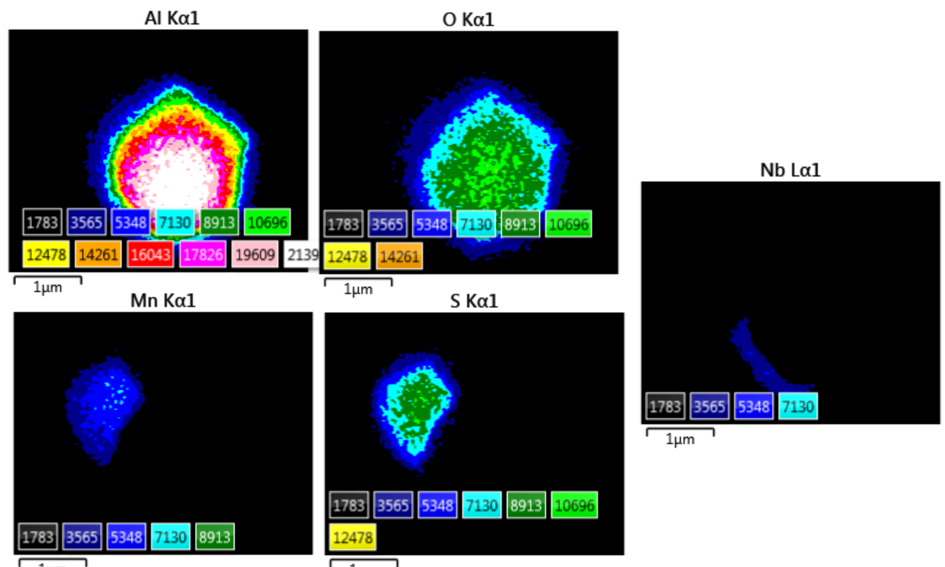
BC

- Coarse precipitation: Al_2O_3, MnS, NbC (homogeneous or co-precipitated)
- Fine precipitation (100-200nm): no fine precipitates (neither NbC nor MnS)







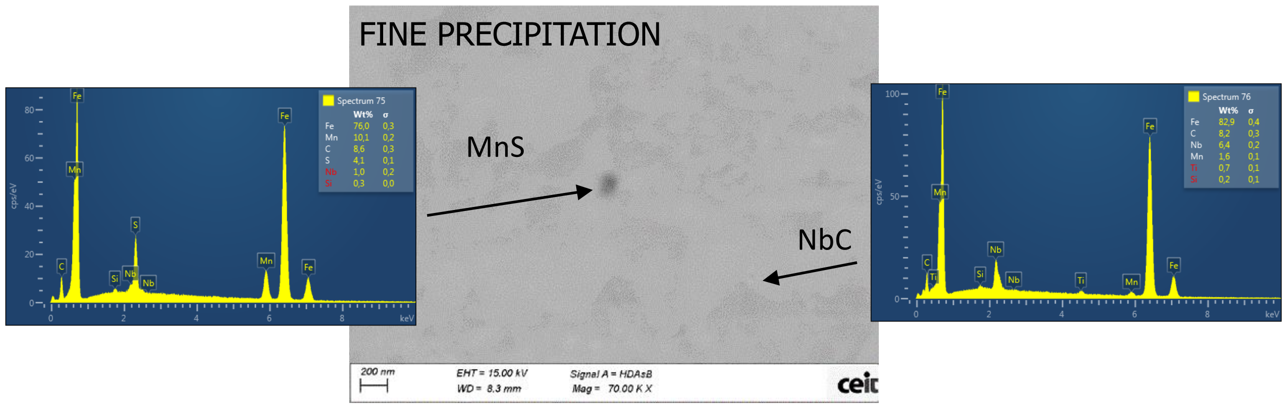


Characterization of precipitation

BC – Main changes

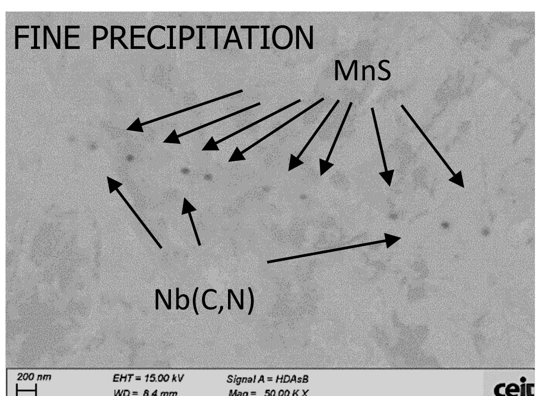
T= 1000ºC

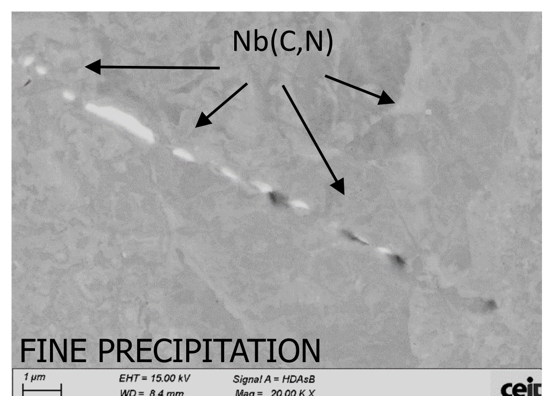
- Fine precipitation (100-200nm): **MnS, Nb(C,N)**



T= 900ºC

- Fine precipitation (100-200nm): **higher density** and aligned in AGB of MnS, Nb(C,N)

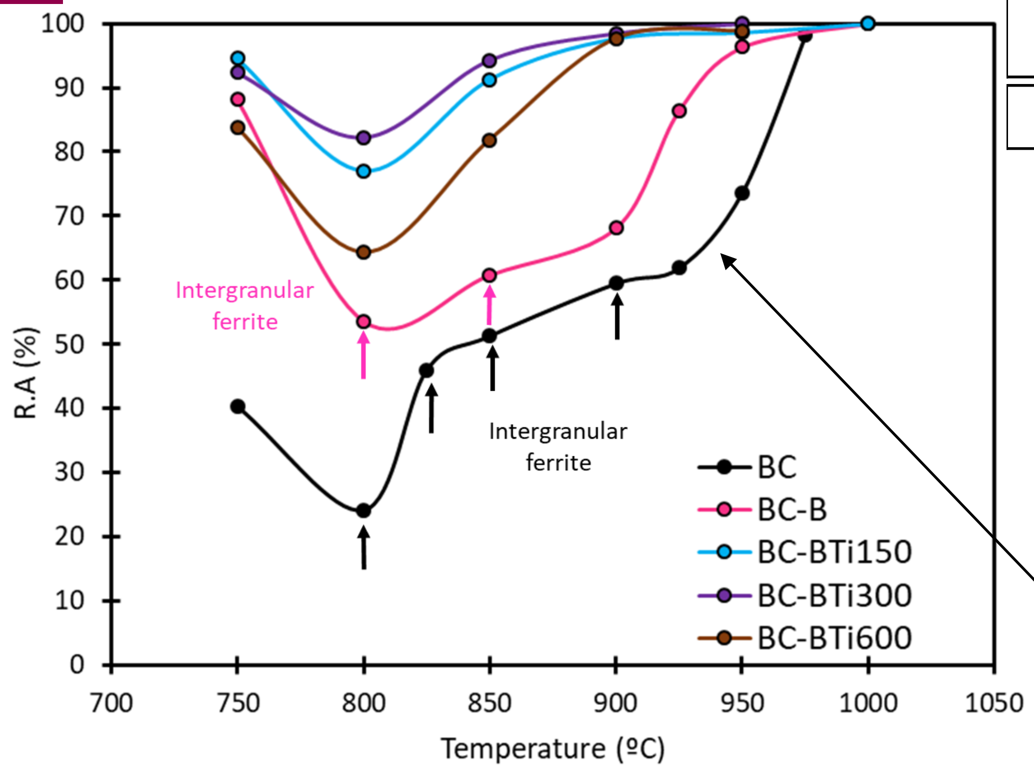




Characterization of precipitation

BC – Main changes

			BC			
Elements	Precipitate	Classification	1325ºC	1000ºC	900ºC	800ºC
Al	Al_2O_3	Coarse precipitation	✓	✓	✓	✓
Nb, Ti	Nb(C,N)	Coarse precipitation	✓	✓	✓	✓
		Fine precipitation (100-200nm)	✗	✓	✓✓	✓✓
	Ti(C,N)	Coarse precipitation	✗	✗	✗	✗
		Fine precipitation (100-200nm)	✗	✗	✗	✗
	(Nb,Ti)(C,N)	Coarse precipitation	✗	✗	✗	✗
		Fine precipitation (100-200nm)	✗	✗	✗	✗
B	BN	Coarse precipitation	✗	✗	✗	✗
		Fine precipitation (100-200nm)	✗	✗	✗	✗
	$Fe_{23}(C,B)_6$	Coarse precipitation	✗	✗	✗	✗
S	MnS	Coarse precipitation	✓	✓	✓	✓
		Fine precipitation (100-200nm)	✗	✓	✓✓	✓✓



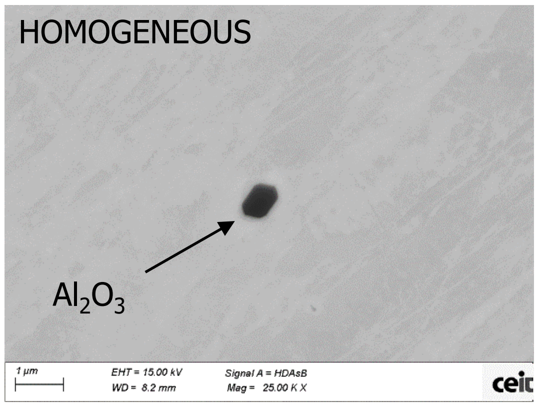
- Fine precipitation of Nb(C,N) and MnS

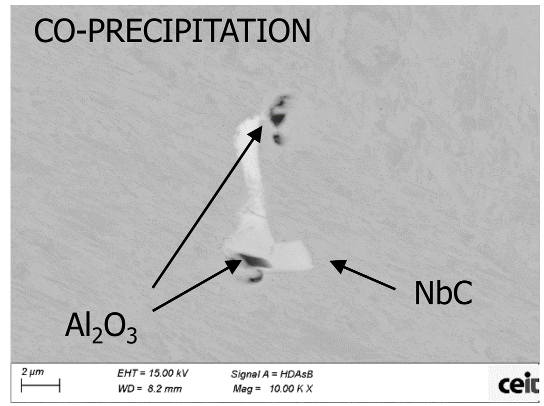
Characterization of precipitation

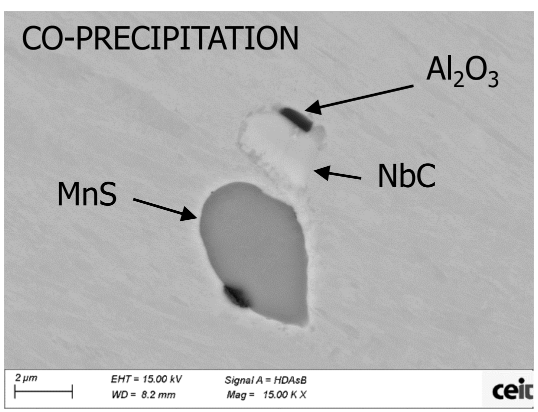
T= 1325ºC

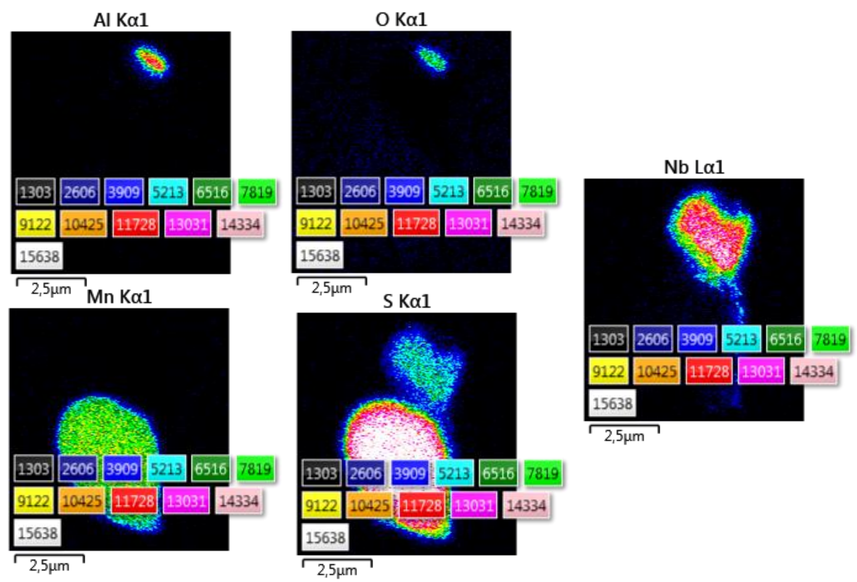
BC-B

- Coarse precipitation: Al_2O_3, MnS, NbC (homogeneous or co-precipitated)
- Fine precipitation (100-200nm): no fine precipitates (neither NbC nor MnS)







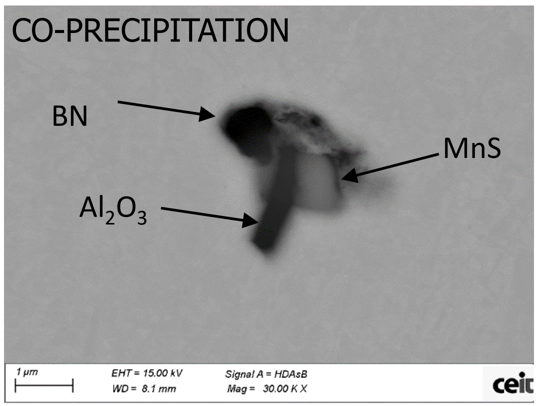


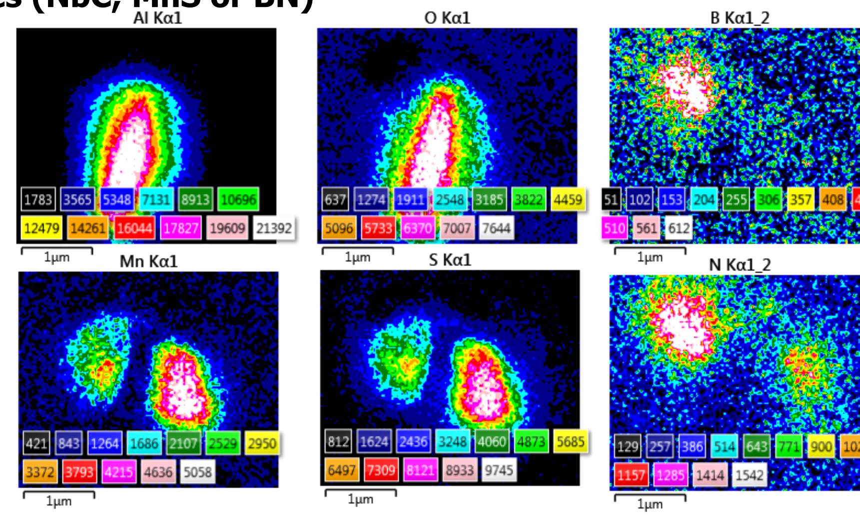
Characterization of precipitation

BC-B – Main changes

T= 1000ºC

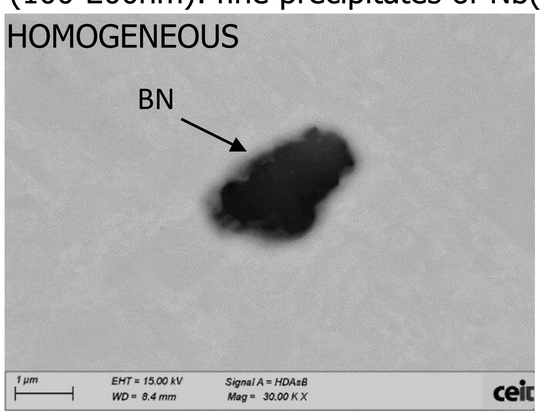
- Coarse precipitation: precipitation of **BN** (always co-precipitated)
- Fine precipitation (100-200nm): **no fine precipitates (NbC, MnS or BN)**

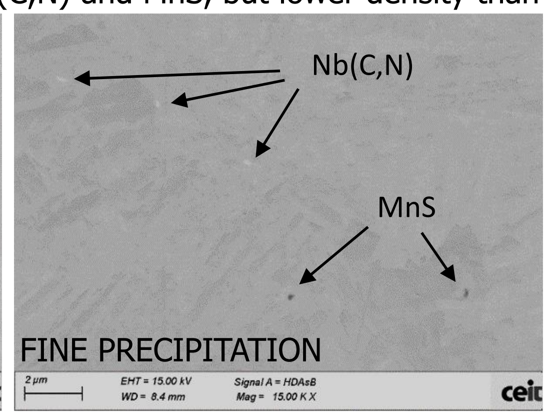




T= 900ºC

- Coarse precipitation: higher density of precipitation of **BN** (even homogeneously precipitated)
- Fine precipitation (100-200nm): fine precipitates of Nb(C,N) and MnS, but lower density than BC





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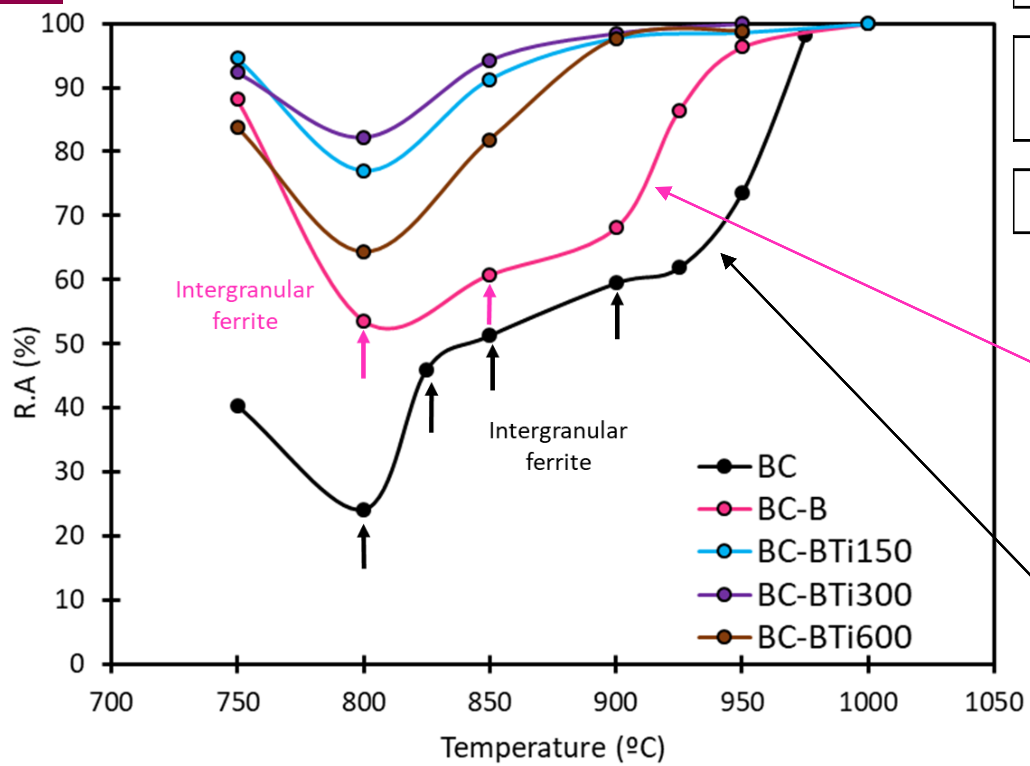
Characterization of precipitation

BC-B – Main changes

Elements	Precipitate	Classification	BC-B 1325ºC	BC-B 1000ºC	BC-B 900ºC	BC-B 800ºC
Al	Al_2O_3	Coarse precipitation	✓	✓	✓	✓
Nb, Ti	Nb(C,N)	Coarse precipitation	✓	✓	✓	✓
		Fine precipitation (100-200nm)	×	×	✓	✓
	Ti(C,N)	Coarse precipitation	×	×	×	×
		Fine precipitation (100-200nm)	×	×	×	×
	(Nb,Ti)(C,N)	Coarse precipitation	×	×	×	×
		Fine precipitation (100-200nm)	×	×	×	×
B	BN	Coarse precipitation	×	✓	✓✓	✓✓
		Fine precipitation (100-200nm)	×	×	×	×
	$Fe_{23}(C,B)_6$	Coarse precipitation	×	×	×	×
S	MnS	Coarse precipitation	✓	✓	✓	✓
		Fine precipitation (100-200nm)	×	×	✓	✓



- For this CR no fine BN precipitation in AGB
- B delays Nb(C,N) and MnS precipitation / B occupies vacancies preventing formation and propagation of cracks

- Fine precipitation of Nb(C,N) and MnS

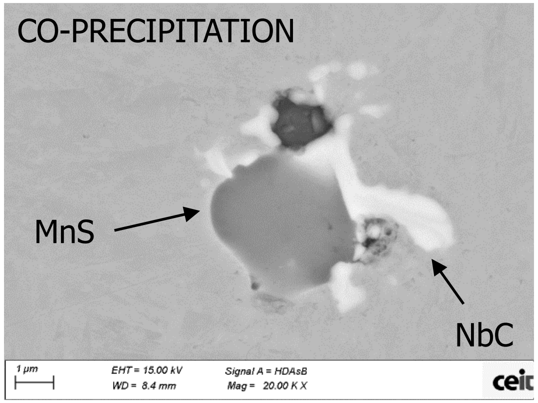
Results and discussion

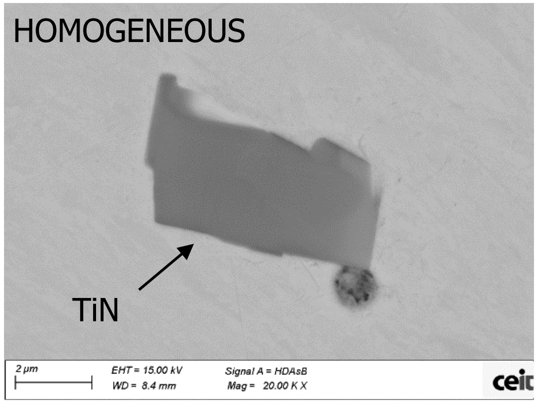
Characterization of precipitation

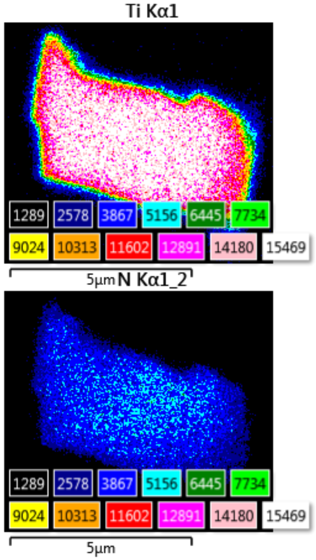
T= 1325ºC

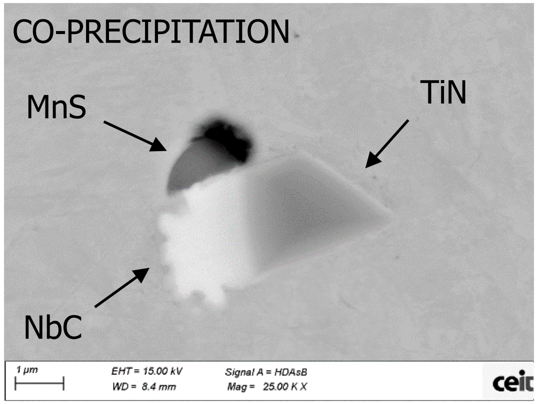
BC-BTi300

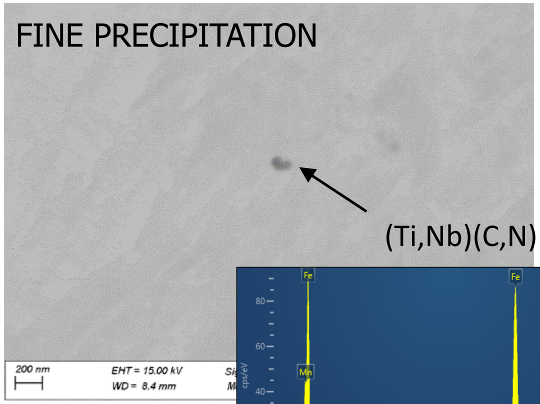
- Coarse precipitation: Al_2O_3, MnS, NbC, **TiN**, (homogeneous or co-precipitated)
- Fine precipitation (100-200nm): **Ti(C,N), (Ti,Nb)(C,N)**

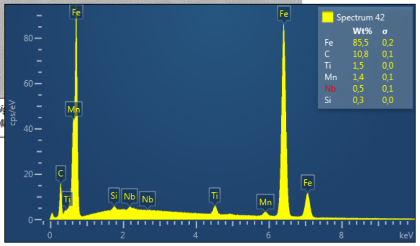










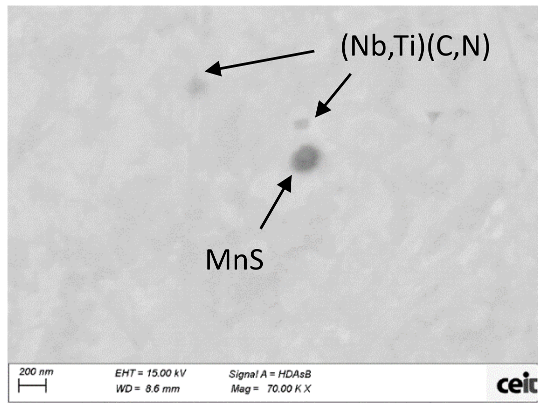


Characterization of precipitation

BC-BTi300 – Main changes

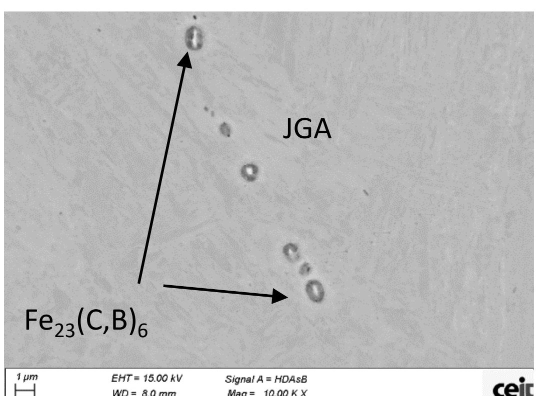
T= 1000ºC

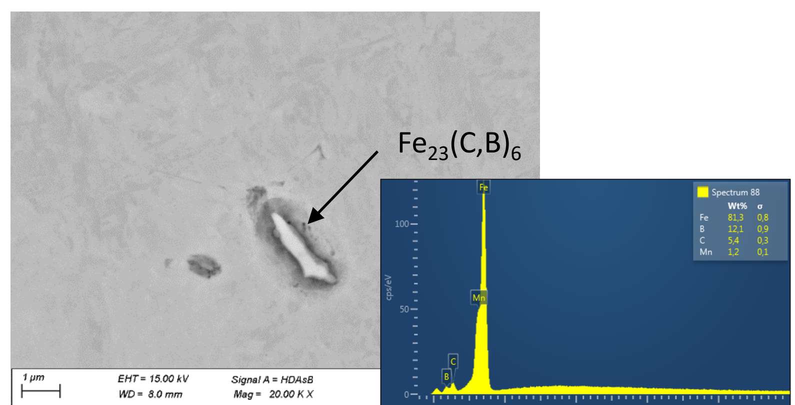
- Coarse precipitation: **NO** precipitation of **BN**
- Fine precipitation (100-200nm): in addition to Ti(C,N), (Ti,Nb)(C,N) → **MnS precipitates**



T= 800ºC

- Coarse precipitation: massive $Fe_{23}(C,B)_6$ precipitation in AGB

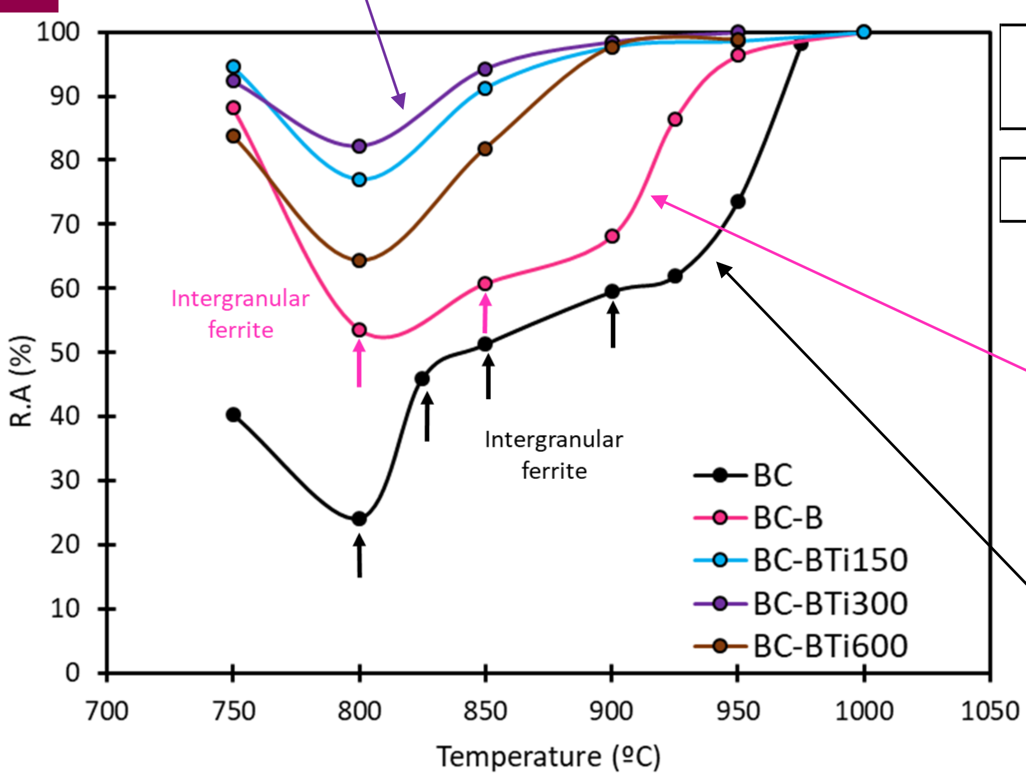




Characterization of precipitation

BC-BTi300 – Main changes

- $Fe_{23}(C,B)_6$ precipitation in AGB (lower B content in ss)



Elements	Precipitate	Classification	BC-BTi300 1325ºC	1000ºC	900ºC	800ºC
Al	Al_2O_3	Coarse precipitation	✓	✓	✓	✓
Nb, Ti	Nb(C,N)	Coarse precipitation	✓	✓	✓	✓
		Fine precipitation (100-200nm)	×	×	×	×
	Ti(C,N)	Coarse precipitation	✓	✓	✓	✓
		Fine precipitation (100-200nm)	✓	✓	✓	✓
	(Nb,Ti)(C,N)	Coarse precipitation	×	×	×	×
		Fine precipitation (100-200nm)	✓	✓	✓	✓
B	BN	Coarse precipitation	×	×	×	×
		Fine precipitation (100-200nm)	×	×	×	×
	$Fe_{23}(C,B)_6$	Coarse precipitation	×	×	×	✓✓
S	MnS	Coarse precipitation	✓	✓	✓	✓
		Fine precipitation (100-200nm)	×	✓	✓	✓

- For this CR no fine BN precipitation in AGB
- B delays Nb(C,N) and MnS precipitation / B occupies vacancies preventing formation and propagation of cracks

- Fine precipitation of Nb(C,N) and MnS

Conclusions

- BC Steel → the extension of the ductility trough in the austenite phase region is related to the precipitation of Nb(C,N), which confirms these grades show a challenging continuous casting process. The choice of bending/straightening conditions must be made carefully

- BC-B steel → B addition can improve hot ductility. This improvement is most probably related to the process of segregation of B and BN precipitation, therefore, great care must be taken with the process conditions, specially with the cooling rate.

- The addition of Ti for the protection of B can greatly improve hot ductility. The optimum Ti addition is that corresponding to the stoichiometric Ti/N ratio. It has been determined:
  - B in ss increases hardenability and in consequence at this cooling rate there is no ferrite transformation
  - Ti addition removes BN precipitation/protects B in ss which improves hot ductility
  - Ductility loss at 800ºC seems to be related to $Fe_{23}(C,B)_6$ precipitation at AGB

Thank you!