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## **Brittle fracture mechanisms of three model low alloy steels chemically representative of macrosegregated forgings**

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# Outline of the presentation

1. Introduction
2. Materials and methods
3. Results and discussion
4. Conclusions



# Industrial context

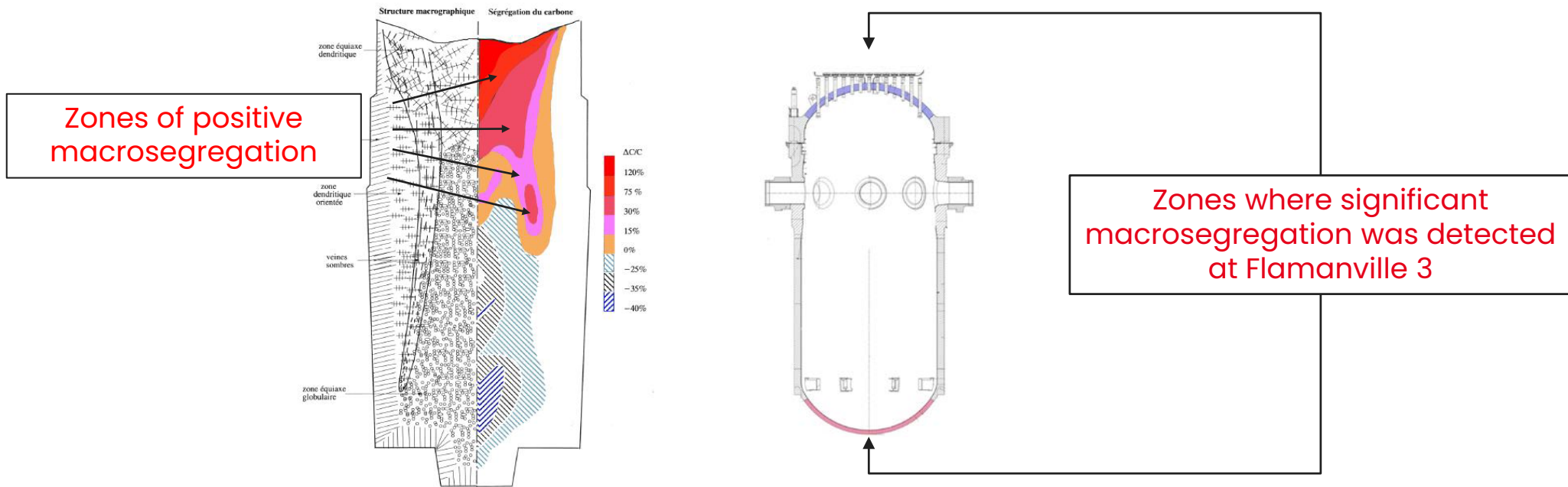
- According to IAEA, ~78% of all operational reactors are Pressurized Water Reactors (PWR)
- PWR feature very large components
  - Reactor pressure vessel
  - Steam generator
- Made from low-alloyed steels (RPV steels), usually forged from heavy ingots

Hinkley Point C EPR reactor pressure vessel (UK)



# Industrial context

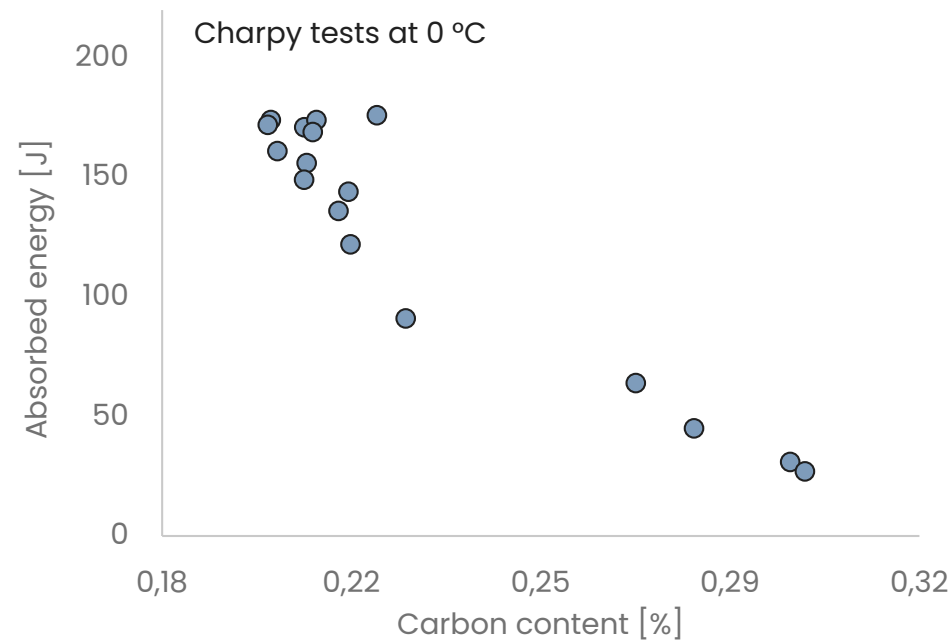
- Heavy ingots feature zones of positive macrosegregation
  - Richer in carbon, alloying elements and impurities
  - Limited segregations ( $\%C_{max} = 0.22\%wt$  in France) can still be present in the final component
- Macrosegregation of the pressure vessel of Flamanville 3 EPR



(Rapport au Groupe permanent d'experts pour les équipements sous pression nucléaires, 2017)

# Industrial context

- Positive segregation associated with the embrittlement of RPV steels
- Destructive material characterizations necessary
  - Ensure structural integrity against brittle failure
  - Expensive and time-consuming



(From the data published by Rapport au Groupe permanent d'experts pour les équipements sous pression nucléaires, 2017)

# Objectives

- Understand the link between macrosegregation, microstructure and brittle failure of RPV steels
  - Material models representing the chemical composition of macrosegregated zones
  - Microstructural characterisation
  - Mechanical characterisation

# Outline of the presentation

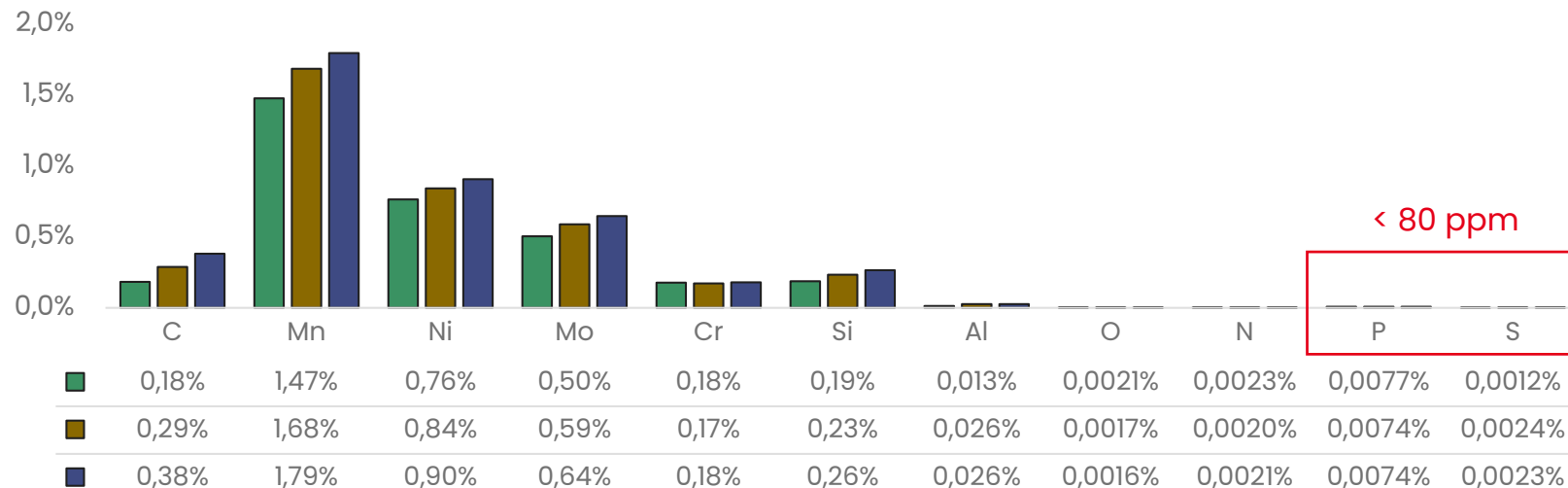
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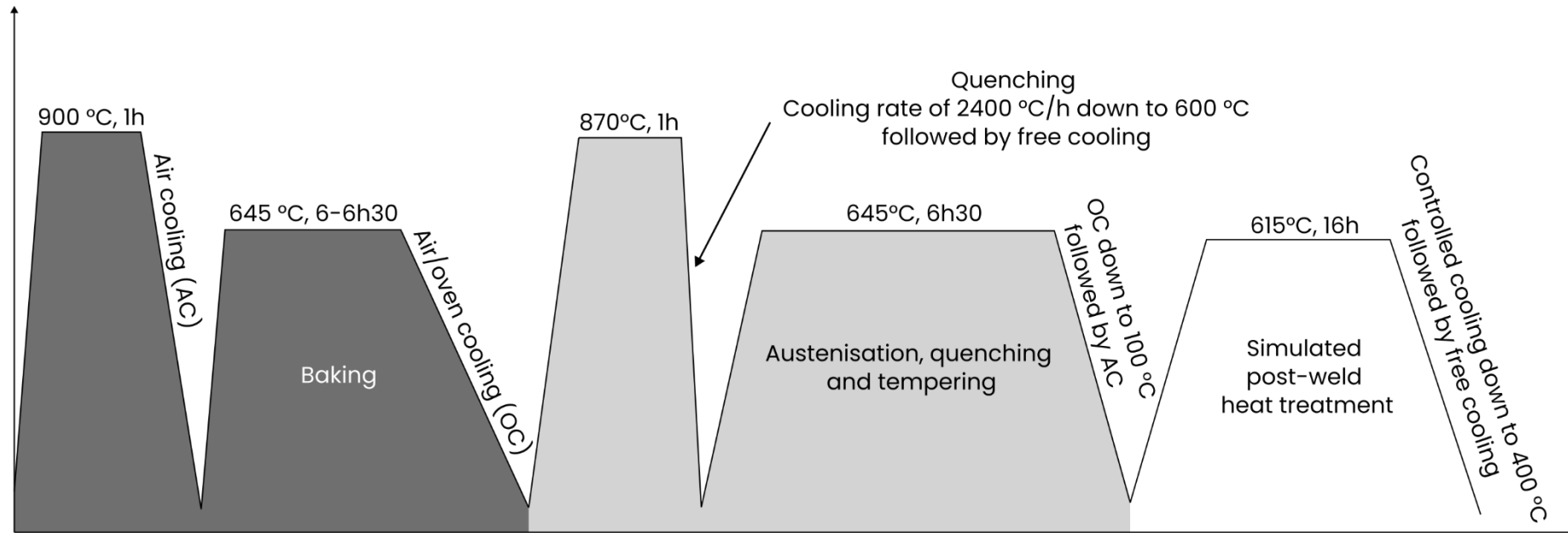
# Materials

- Three **model materials** representing the chemical composition of macrosegregated zones
  - **Non-segregated/nominal composition (0,18%C)**, similar to 18MND5/ASME A508 Gr3 Cl2
  - **Moderate macrosegregation (0,29%C)**
  - **Intense macrosegregation (0,38%C)**
- Alloying elements content increases linearly with carbon content
- Casting of small ingots (~ 50 kg)



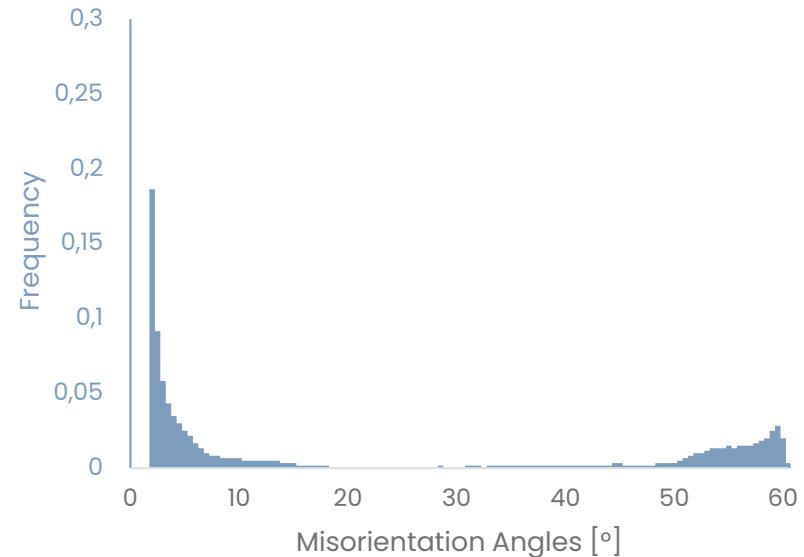
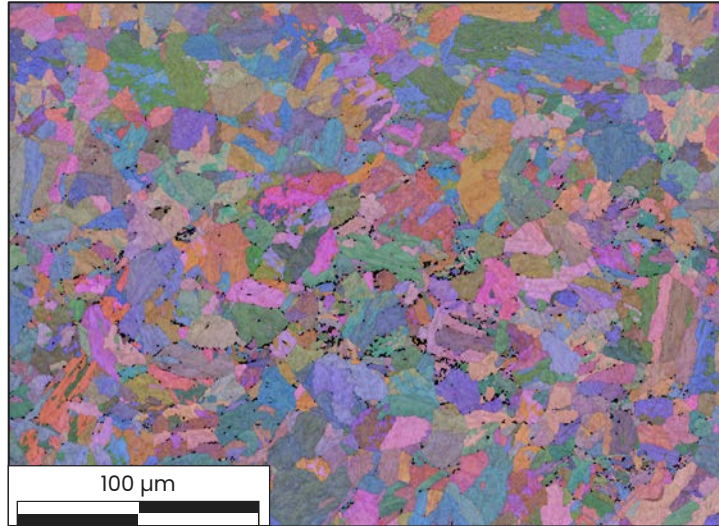
# Materials

- Homogenisation heat treatment carried out before forging (1200 °C, 24h)
  - Separate the effects of macro and microsegregation
  - Not commonly used for industrial components
- Forging at 1180 °C
- Heat treatment simulating the one used for industrial components



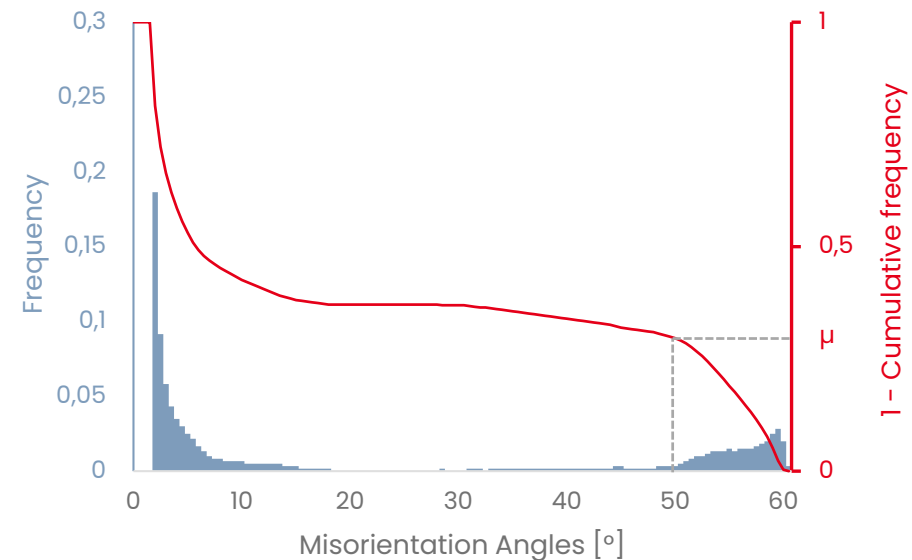
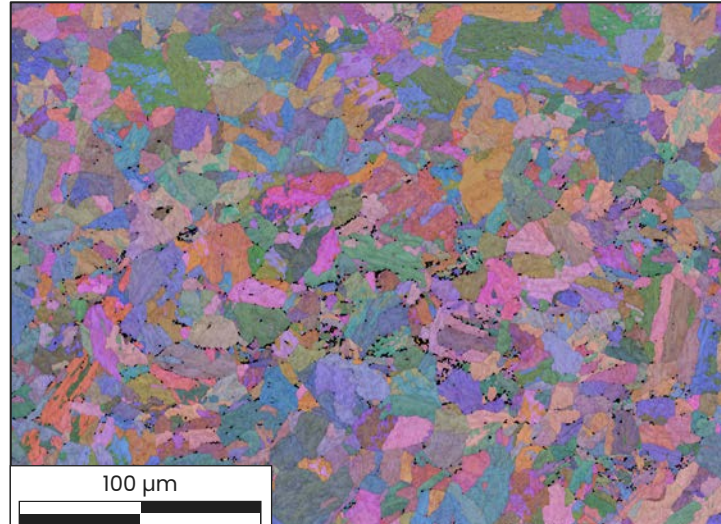
# Microstructural characterisation

- Microstructural evolution quantified based on misorientation angles obtained via EBSD
  - Lower bainitic/martensitic microstructures feature a high frequency of 50–60° misorientation angles (Gourgues, 2000; Zajac et al., 2005)



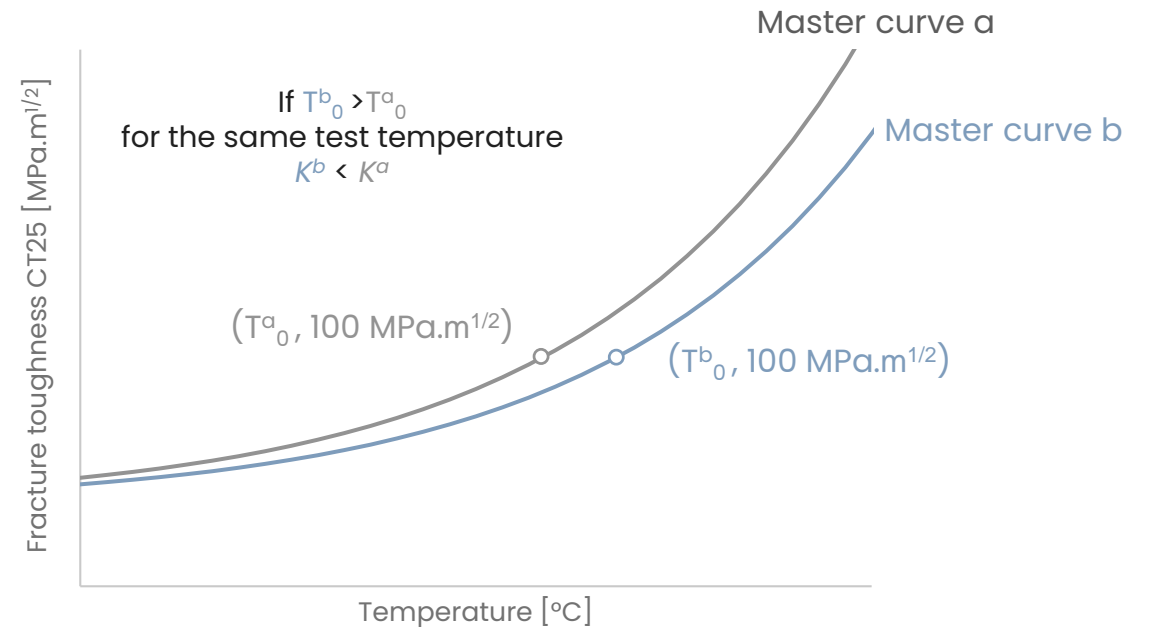
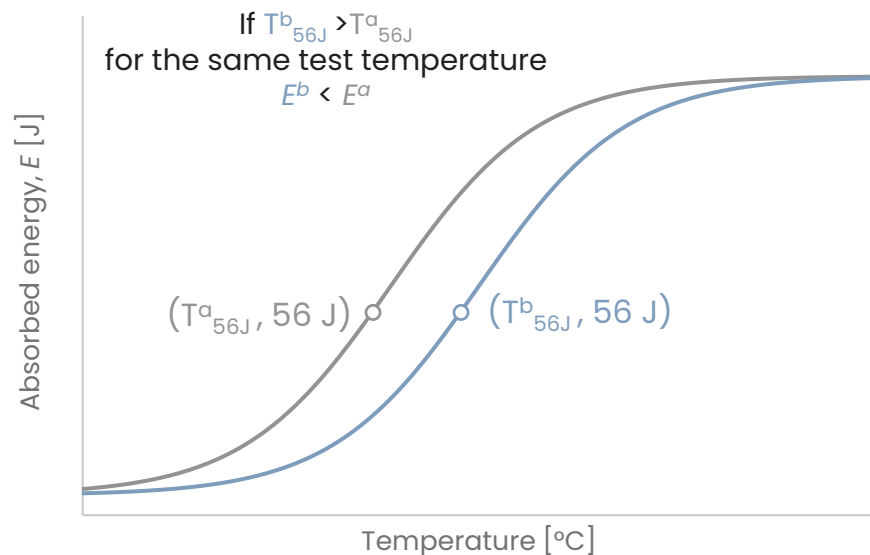
# Microstructural characterisation

- Microstructural evolution quantified based on misorientation angles obtained via EBSD
  - Lower bainitic/martensitic microstructures feature a high frequency of 50–60° misorientation angles (Gourgues, 2000; Zajac et al., 2005)
- Microstructural parameter  $\mu$  calculated as the cumulative frequency between 50–60°
  - Increase in  $\mu$  indicates evolution towards lower bainitic/martensitic microstructure



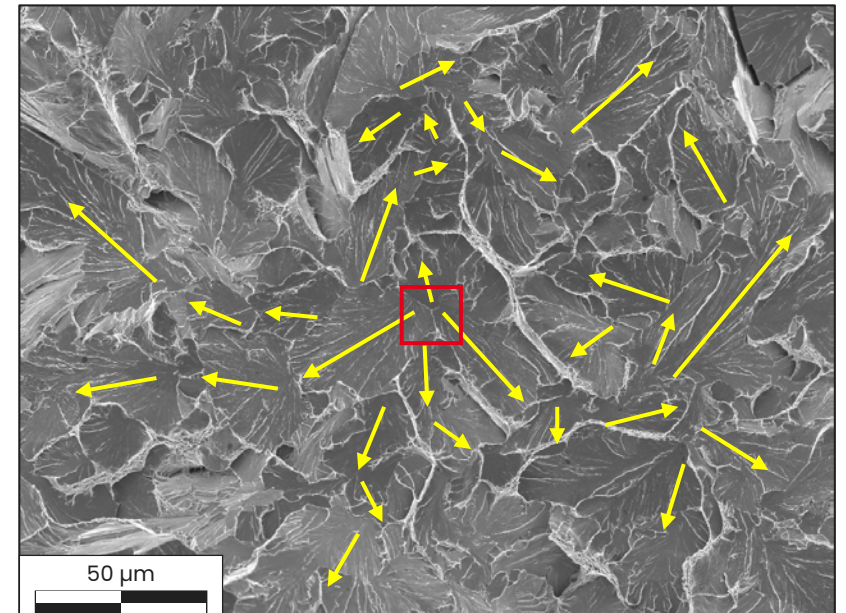
# Mechanical tests

- Charpy and fracture toughness tests
  - Standard V-Charpy specimens
  - CT specimens ( $B = 12.5 \text{ mm}$ )
- Temperatures  $T_{56J}$  and  $T_0$  from Master curve (ASTM E1921) used to quantify embrittlement
  - Increase in  $T_{56J}/T_0 \rightarrow$  embrittlement



# Fractographic analyses

- Carried out for both Charpy and CT specimens at the ductile-to-brittle transition
  - **Non-segregated (0,18%C)**
    - 5 specimens (2 Charpy + 3 CT)
  - **Moderate macrosegregation (0,29%C)**
    - 6 specimens (2 Charpy + 5 CT)
  - **Intense macrosegregation (0,38%C)**
    - 6 specimens (2 Charpy + 4 CT)
- Type of brittle fracture (cleavage or intergranular)
- Initiation site of brittle fracture
  - Determined based on cleavage river marks
  - Qualitative analyses of chemical composition via EDX



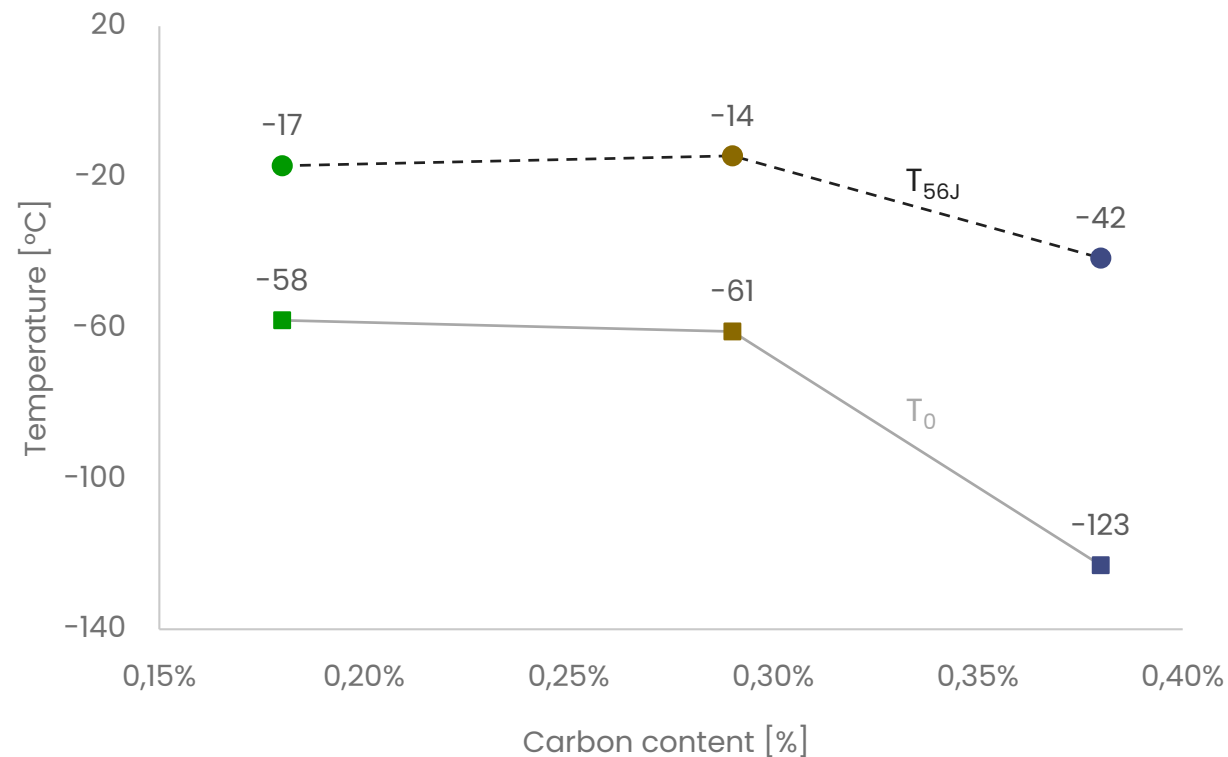
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# Mechanical tests

- Non-linear evolution of  $T_{56J}$  (Charpy) and  $T_0$  (fracture toughness)
  - Similar temperatures for **non-segregated** and **moderately macrosegregated** materials
  - **Intensely macrosegregated** material has the lowest temperatures (least brittle)

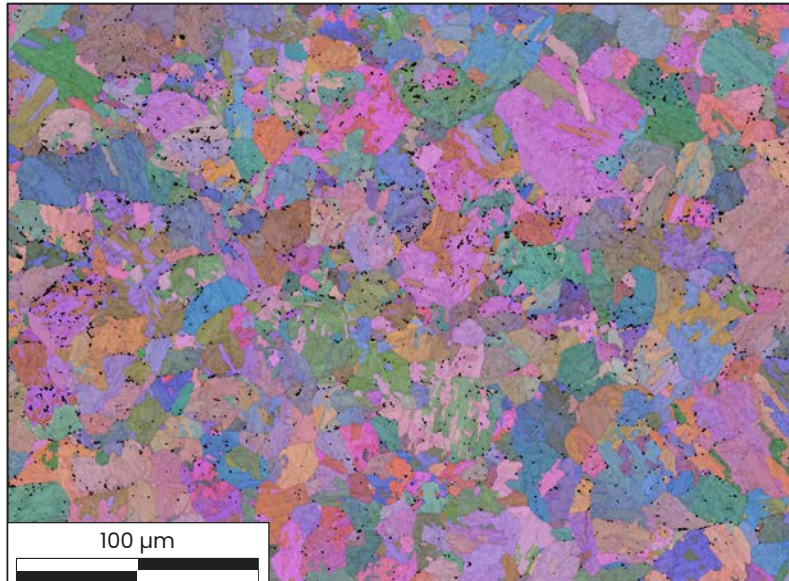




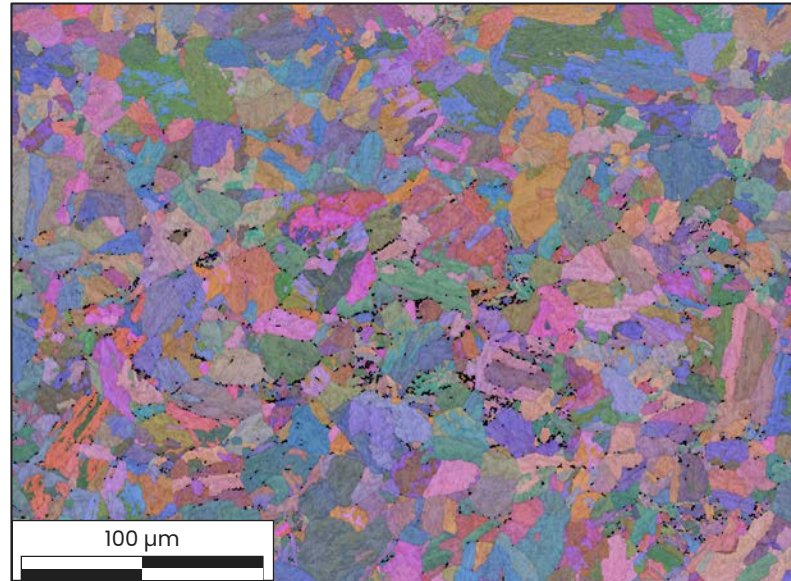
# Microstructural evolution

- Microstructure depends on the macrosegregation level
  - Usual bainitic microstructure for **non-segregated** and **moderately macrosegregated** materials
  - **Intensely macrosegregated** material is lower bainitic/martensitic

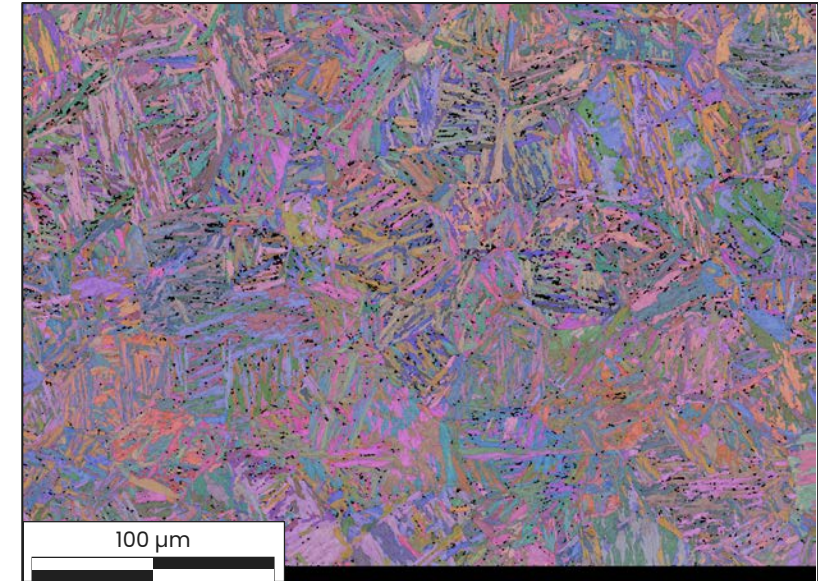
**Non-segregated**



**Moderate macrosegregation**

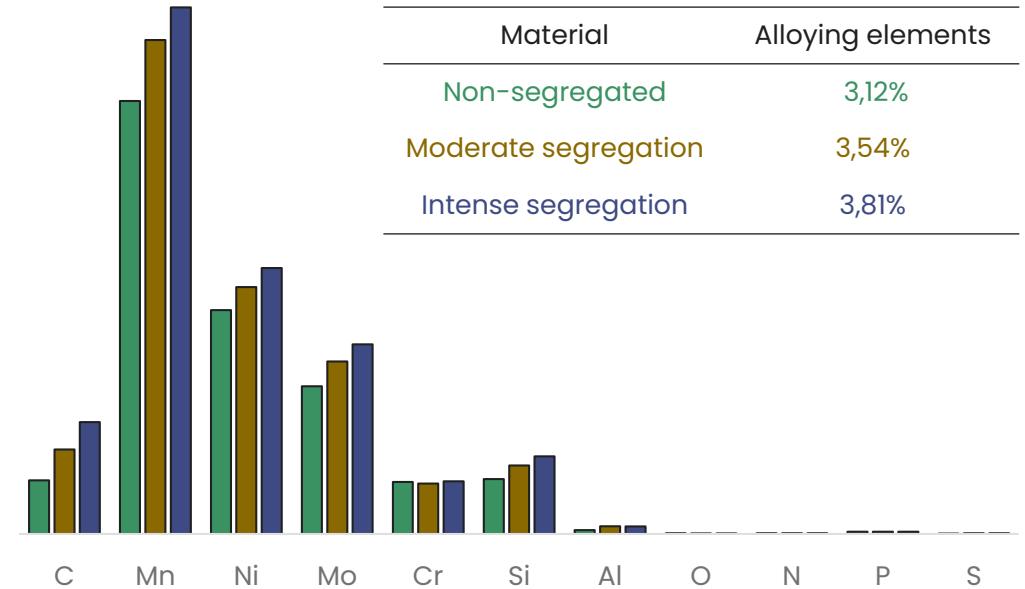
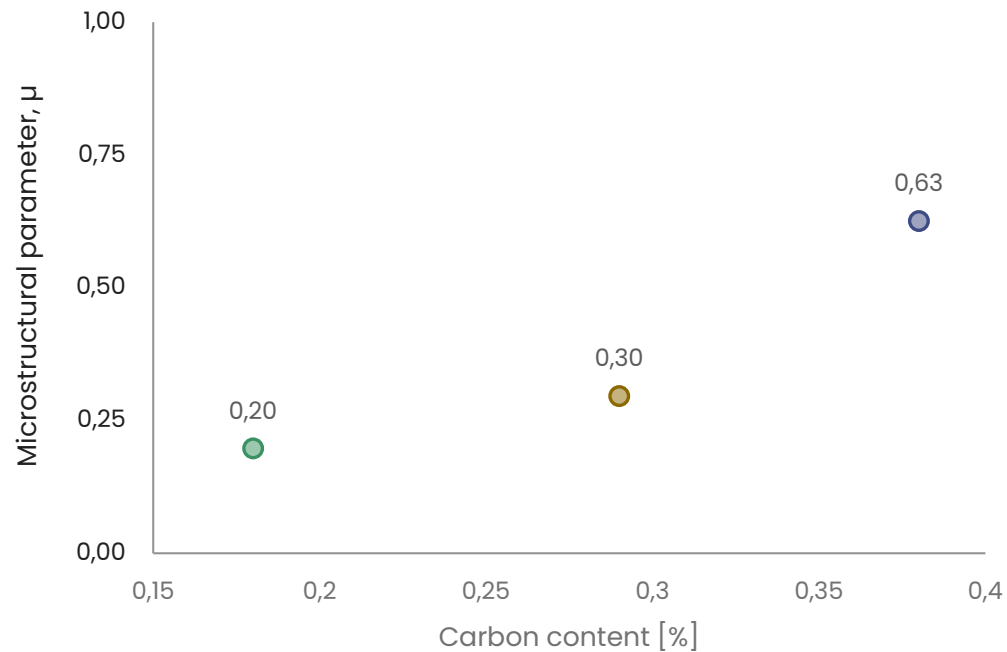


**Intense macrosegregation**



# Microstructural evolution

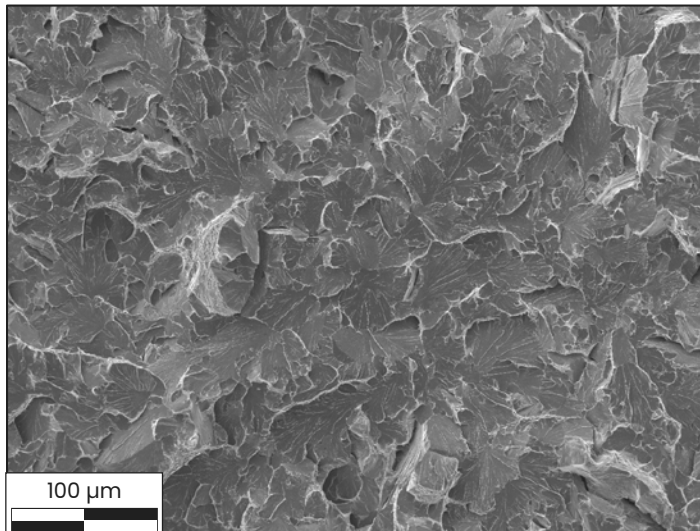
- Increase in  $\mu$   $\rightarrow$  microstructure evolves towards lower bainite/martensite
- Consistent with the increase in hardenability with the increase in alloying elements
- Martensite can be more resistant to cleavage than bainite for RPV steels (Marini et al., 2015)



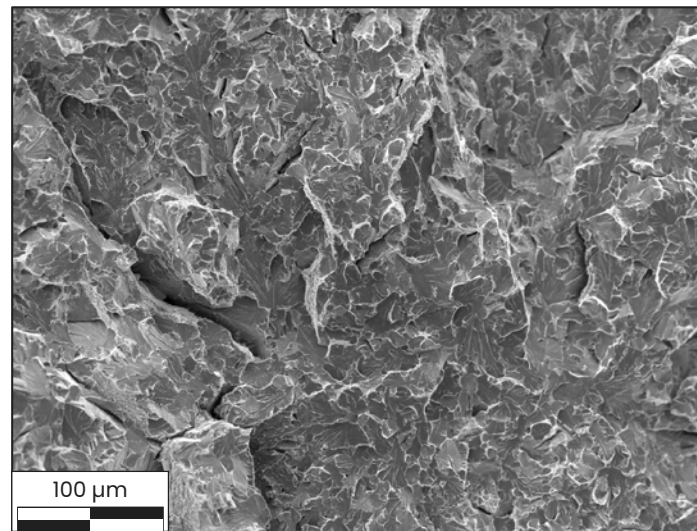
# Failure mode

- Failure mode depends on the macrosegregation level
  - Cleavage for **non-segregated** and **moderately macrosegregated** materials
  - **Intensely macrosegregated** material feature both cleavage and intergranular failure
    - Intergranular failure possibly due to increase in the cleavage resistance

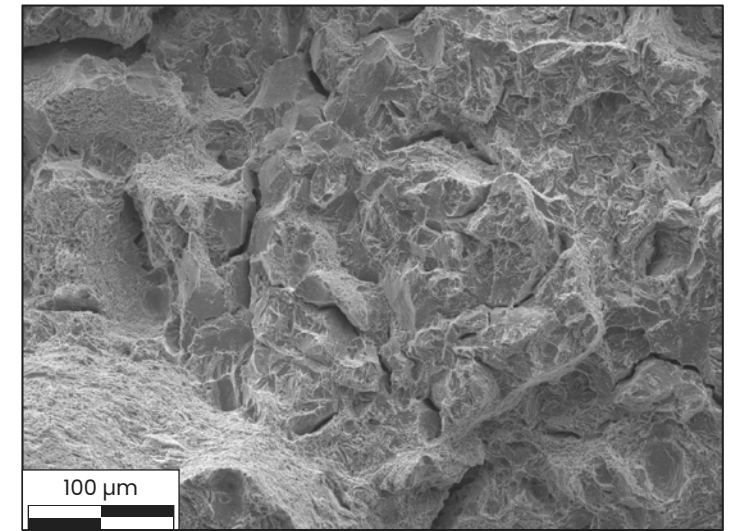
**Non-segregated**



**Moderate macrosegregation**



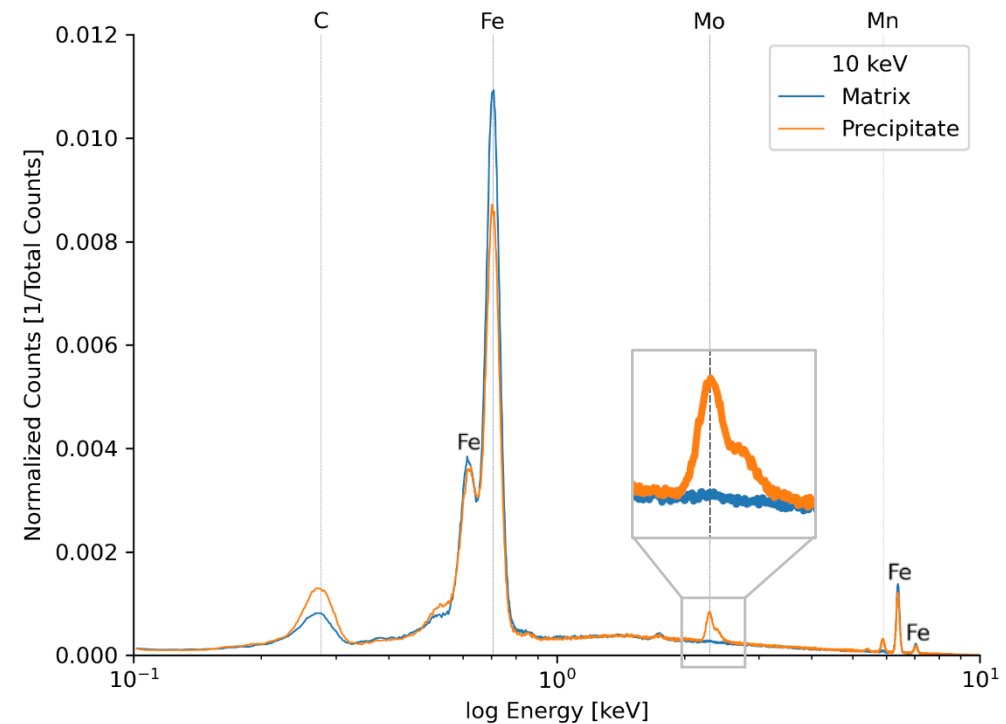
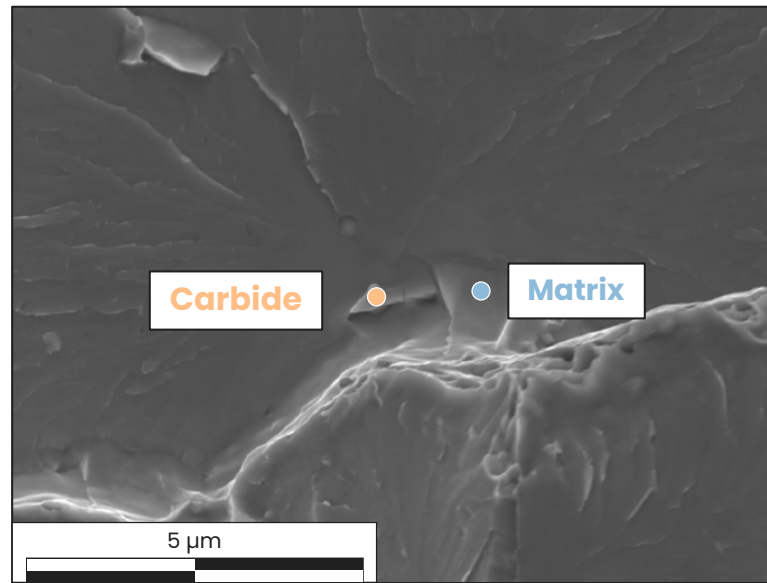
**Intense macrosegregation**



# Initiation sites

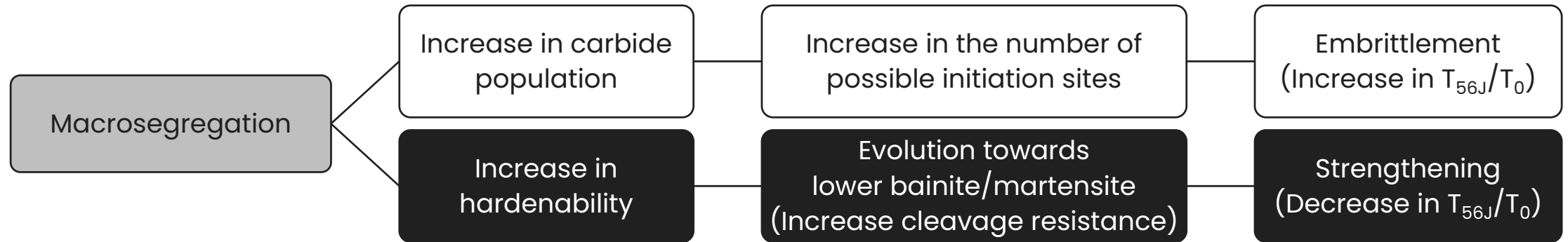
- Determination possible only for **non-segregated** and **moderately macrosegregation**
- Carbides are the dominant microstructural feature at the origin of failure (7/11 cases)
  - Mostly Mo-enriched (5/11)
  - Always found near grain boundaries

## Moderate macrosegregation



# Hypothesis for the evolution of temperatures

- Presence of two effects associated with macrosegregation



- For **moderately macrosegregated** material, both effects have similar magnitudes
  - Temperatures  $T_{56J}$  and  $T_0$  similar to those of **non-segregated** material
- For **intensely macrosegregated** material, the strengthening effect is dominant
  - Lowest temperatures  $T_{56J}$  and  $T_0$
  - Likely associated with homogenisation heat treatment
    - Less microsegregation → homogeneous chemical composition → microstructure globally more hardenable

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# Conclusions

- Unexpectedly, the **intensely macrosegregated** material is the least brittle
  - Similar results for **non-segregated** and **moderately macrosegregated** materials
- Macrosegregation has two different effects
  - Embrittlement due to the increase in the carbide population
  - Strengthening due to the evolution of the microstructure towards lower bainite/martensite
- Unexpected evolution of  $T_{56J}$  and  $T_0$  explained by the competition between those effects
  - For **moderately macrosegregated** material, effects cancel out
  - For **intensely macrosegregated** material, strengthening more pronounced than embrittlement
- Analyses limited to homogenised model materials, **do not represent industrial materials**
  - Different thermomechanical history, absence of homogenisation, ingot size, etc.

# Future works

- Similar analyses on industrial materials
  - Specimens machined from macrosegregated steam generator (sacrificial component)
- Modelling of the effects of microsegregation based on the local approach to fracture



# References

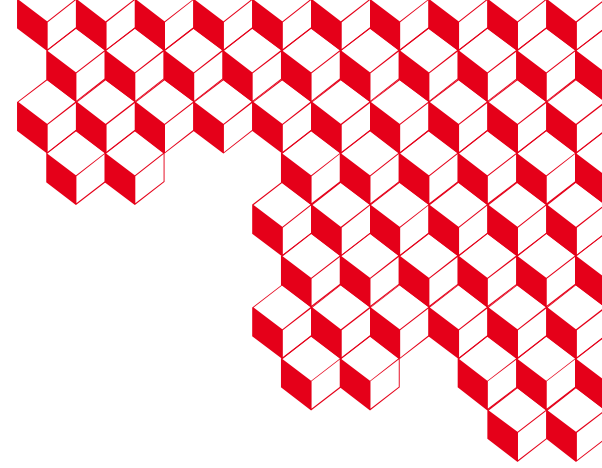
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# Thank you !

**Photo credits :**

Hinkley Point C reactor pressure vessel, © EDF Energy

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