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

Cainã BEMFICA¹, Ludovic VINCENT¹, Bernard MARINI¹, Gaëlle LEOPOLD², Patrick LE DELLIU²,
Frédéric DELABROUILLE²

¹Université Paris-Saclay, CEA, Service de Recherche en Matériaux et procédés Avancés, 91191, Gif-sur-Yvette, France

²EDF, R&D, Renardières Ecuelles, Département MMC, 77250, Orvanne, France

Outline of the presentation

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



Industrial context

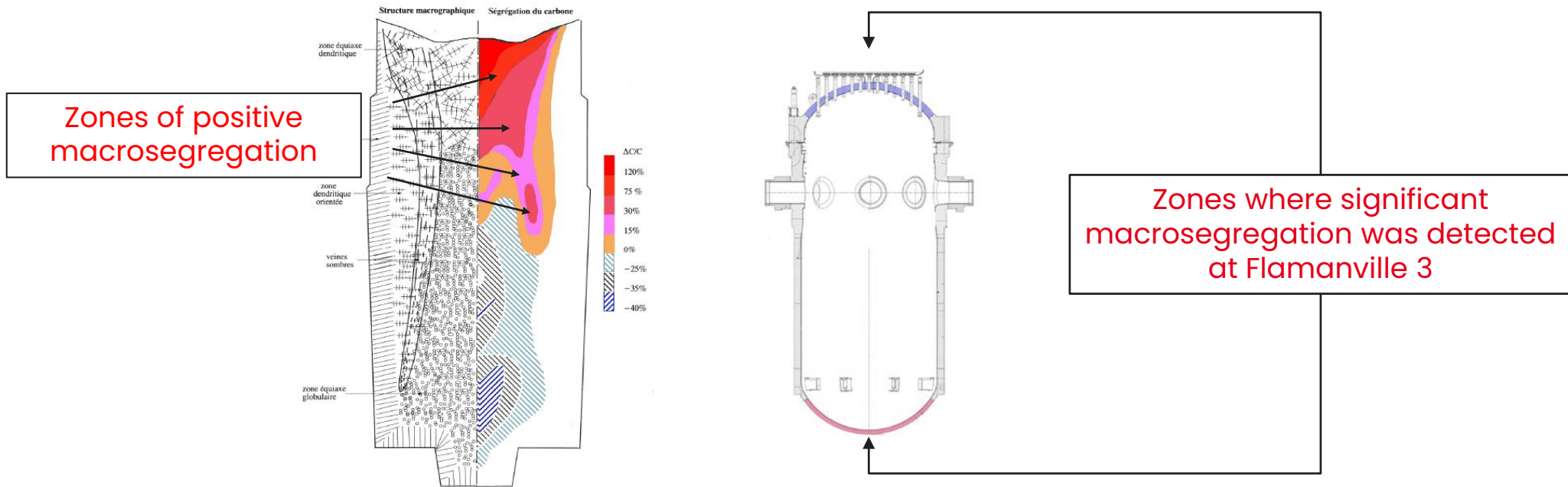
- According to IAEA, ~78% of all operational reactors are Pressurized Water Reactors (PWR)
- PWR feature very large components
 - Reactor pressure vessel
 - Steam generator
- Made from low-alloyed steels (RPV steels), usually forged from heavy ingots

Hinkley Point C EPR reactor pressure vessel (UK)



Industrial context

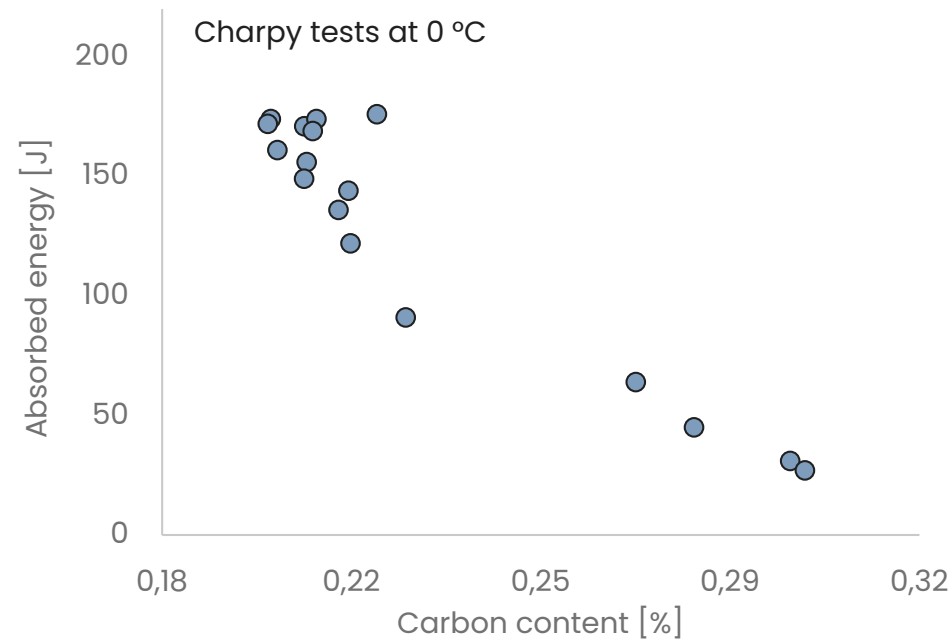
- Heavy ingots feature zones of positive macrosegregation
 - Richer in carbon, alloying elements and impurities
 - Limited segregations ($\%C_{\max} = 0.22\%wt$ in France) can still be present in the final component
- Macrosegregation of the pressure vessel of Flamanville 3 EPR



(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

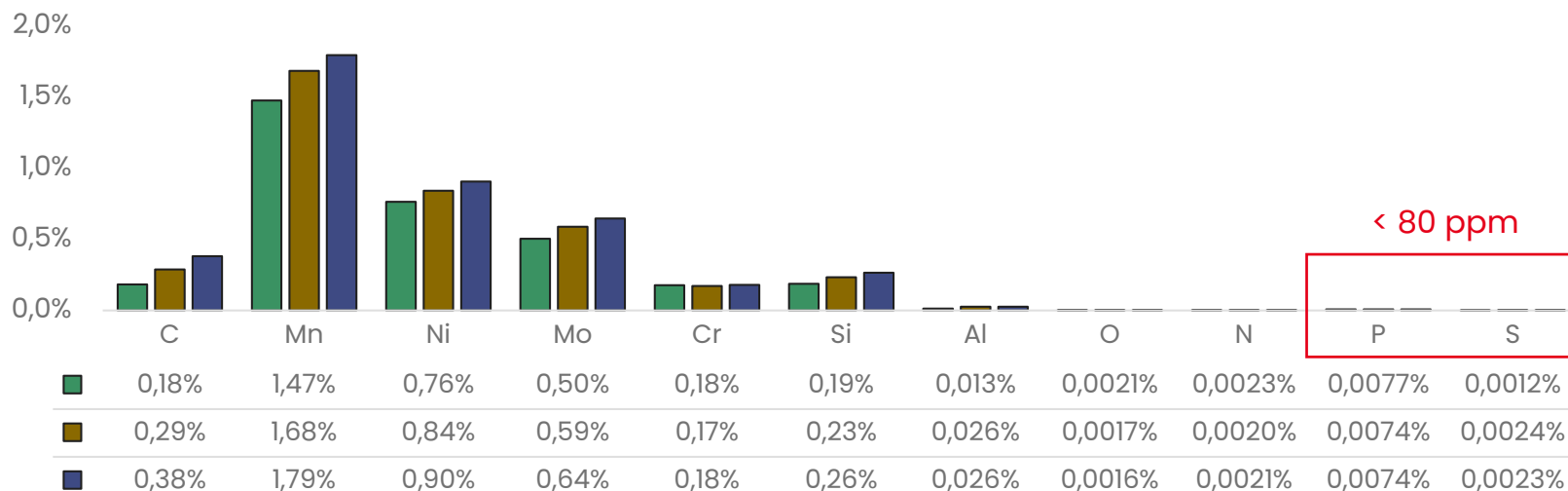
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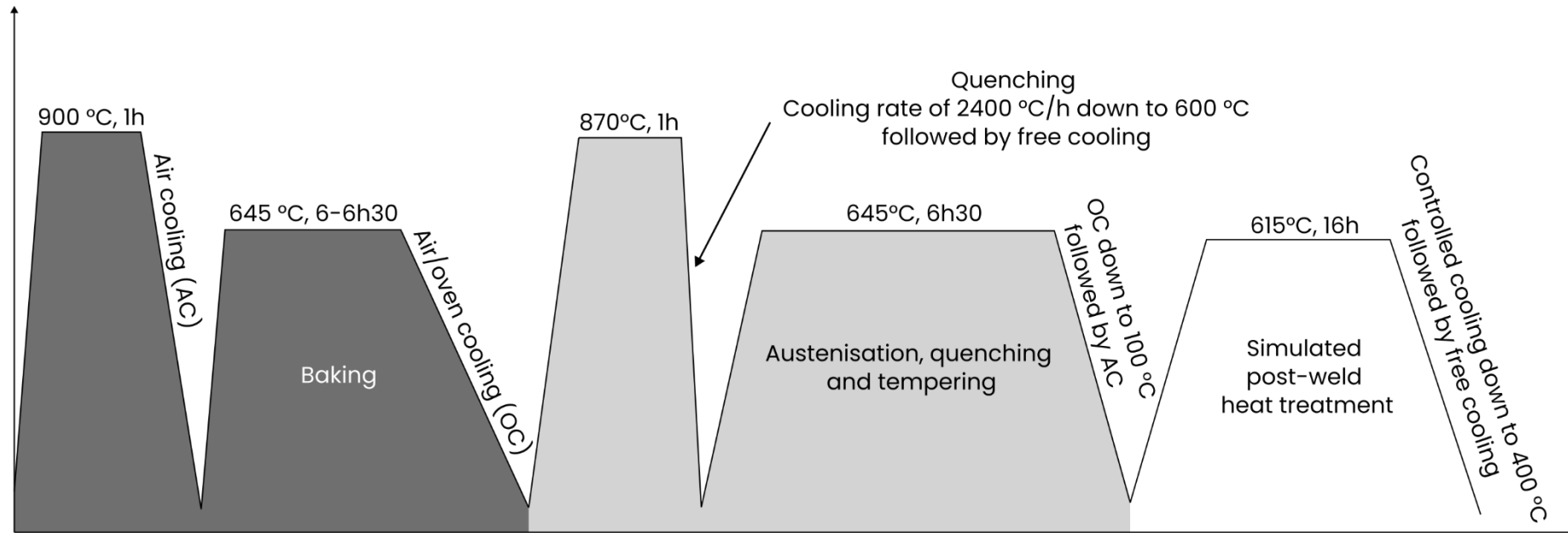
Materials

- 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)



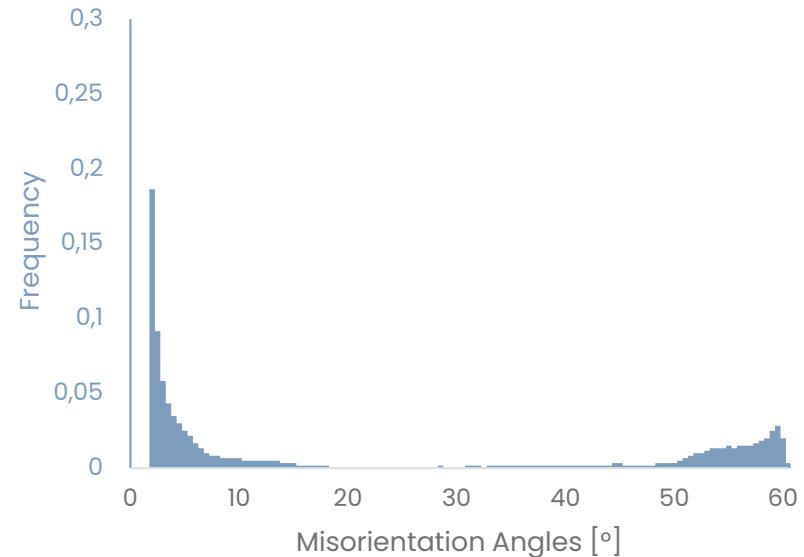
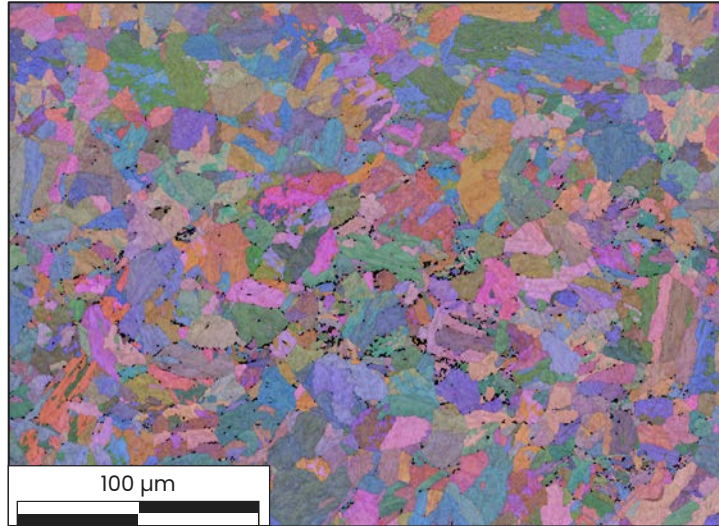
Materials

- 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



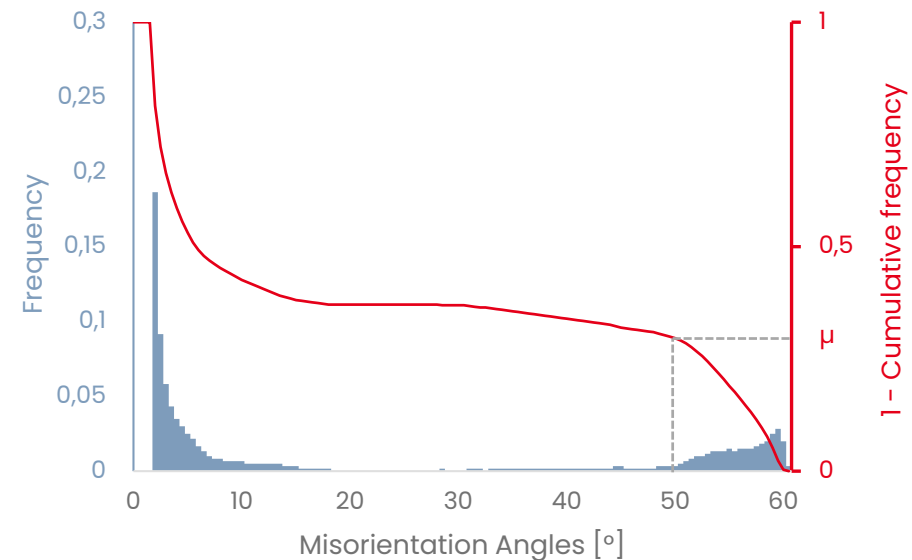
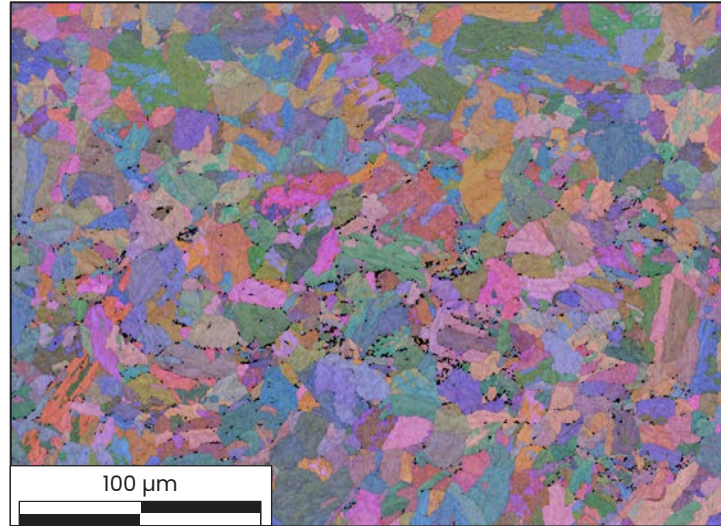
Microstructural characterisation

- 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)



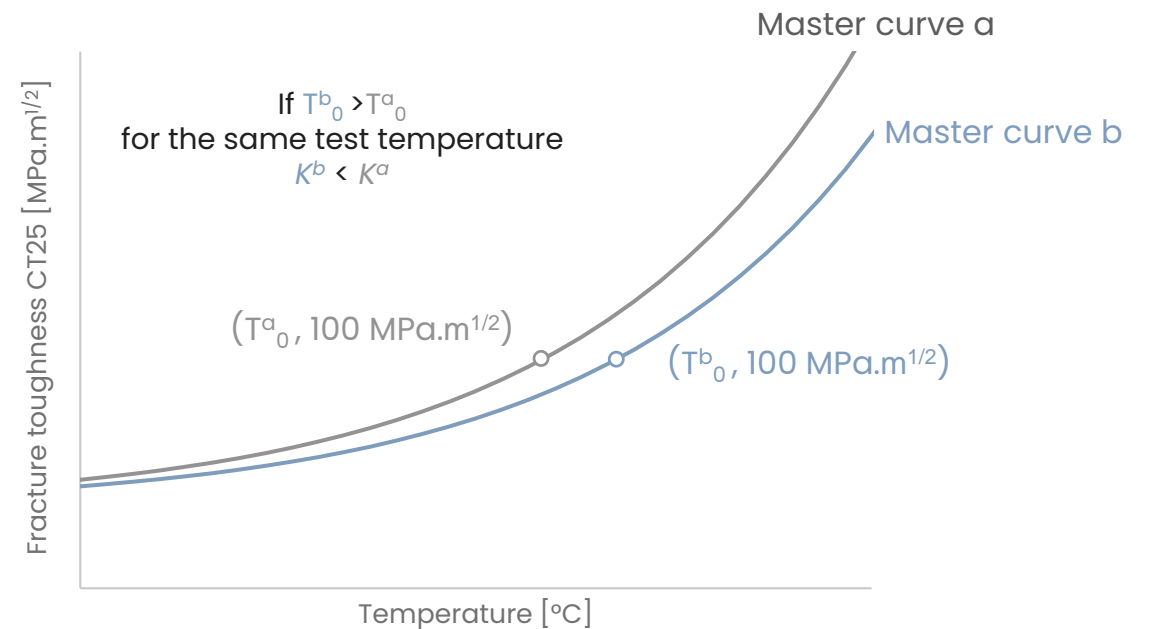
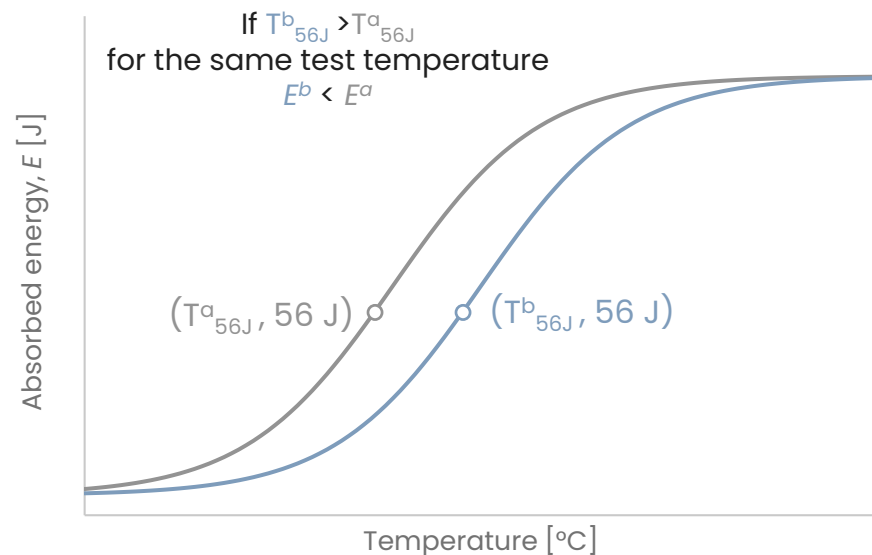
Microstructural characterisation

- 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 μ calculated as the cumulative frequency between 50–60°
 - Increase in μ indicates evolution towards lower bainitic/martensitic microstructure



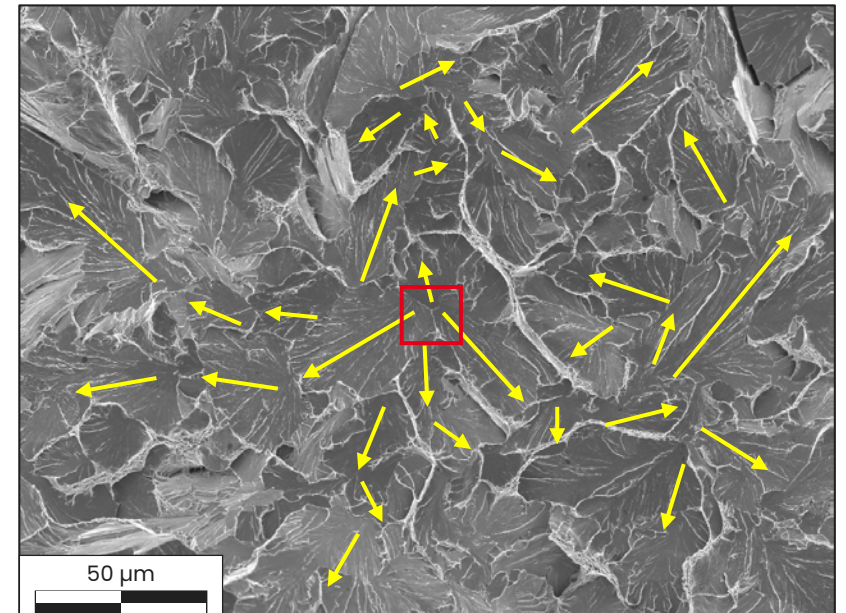
Mechanical tests

- 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



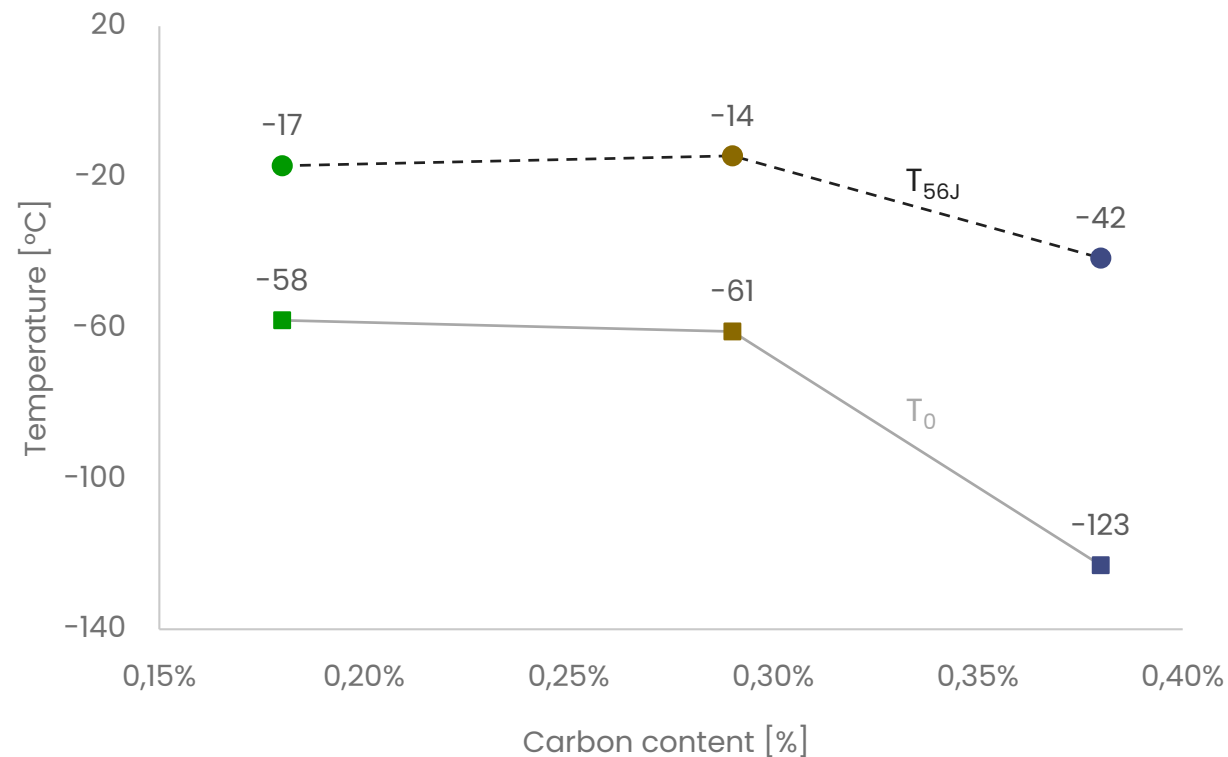
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Mechanical tests

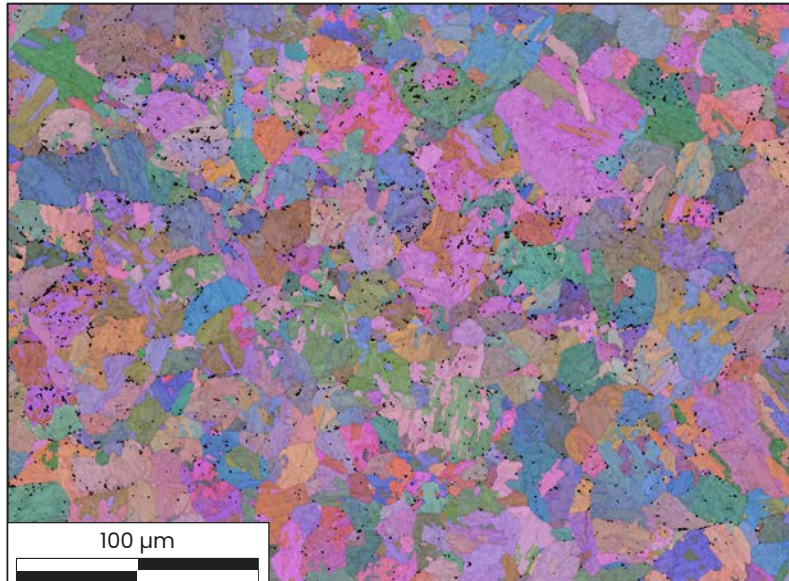
- Non-linear evolution of T_{56J} (Charpy) and T_0 (fracture toughness)
 - Similar temperatures for **non-segregated** and **moderately macrosegregated** materials
 - **Intensely macrosegregated** material has the lowest temperatures (least brittle)



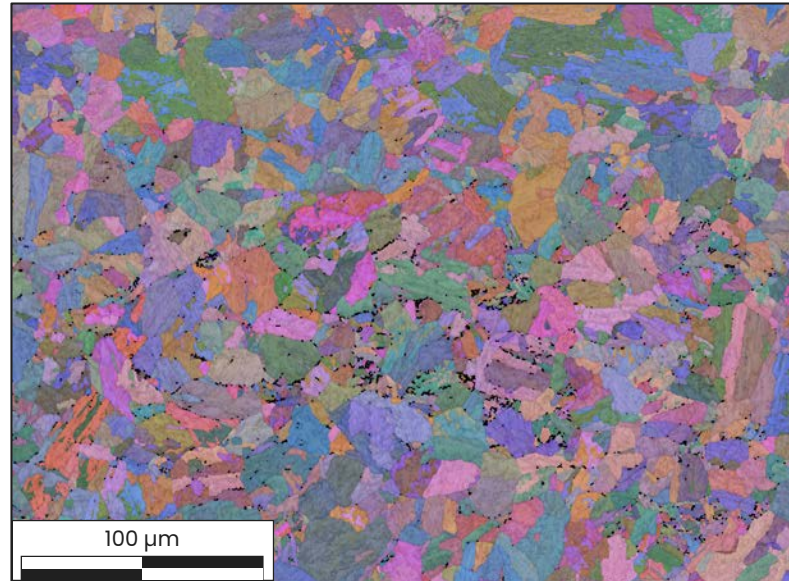
Microstructural evolution

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

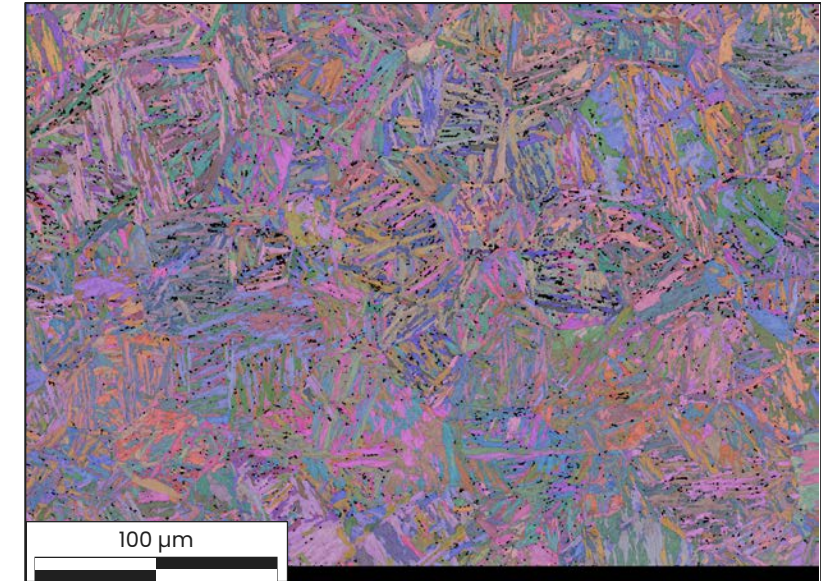
Non-segregated



Moderate macrosegregation

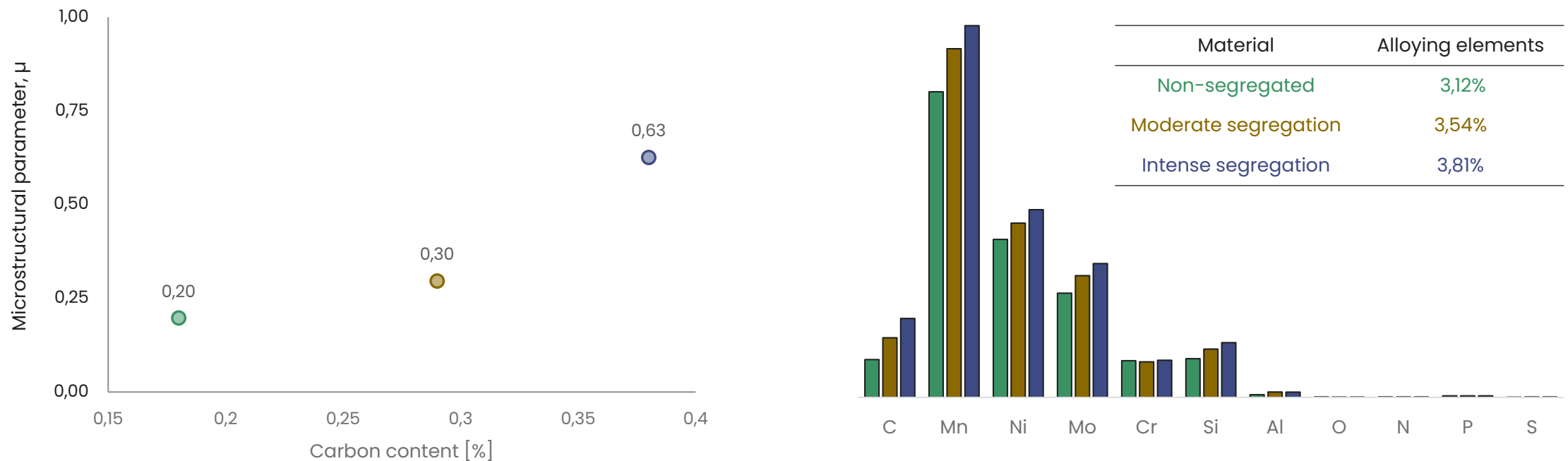


Intense macrosegregation



Microstructural evolution

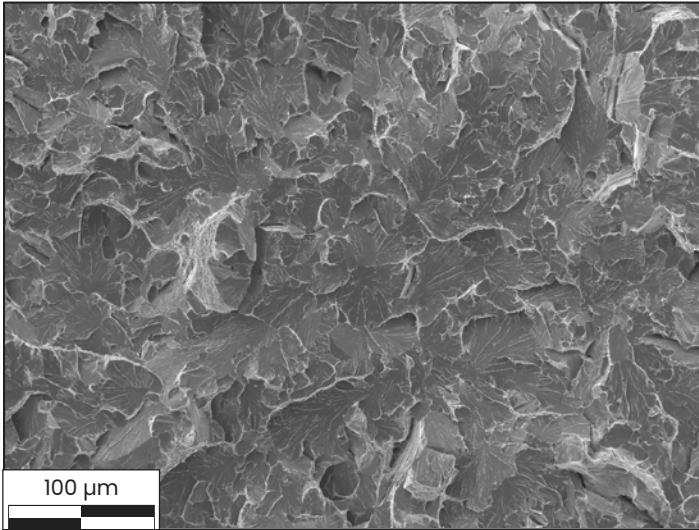
- Increase in μ → microstructure evolves towards lower bainite/martensite
- Consistent with the increase in hardenability with the increase in alloying elements
- Martensite can be more resistant to cleavage than bainite for RPV steels (Marini et al., 2015)



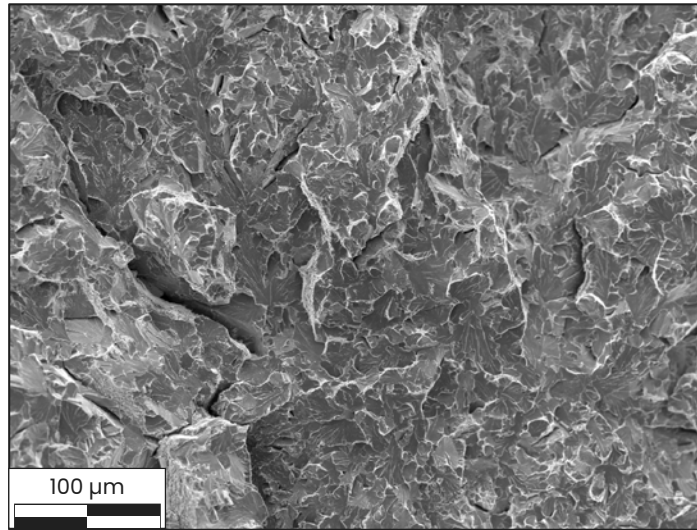
Failure mode

- 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

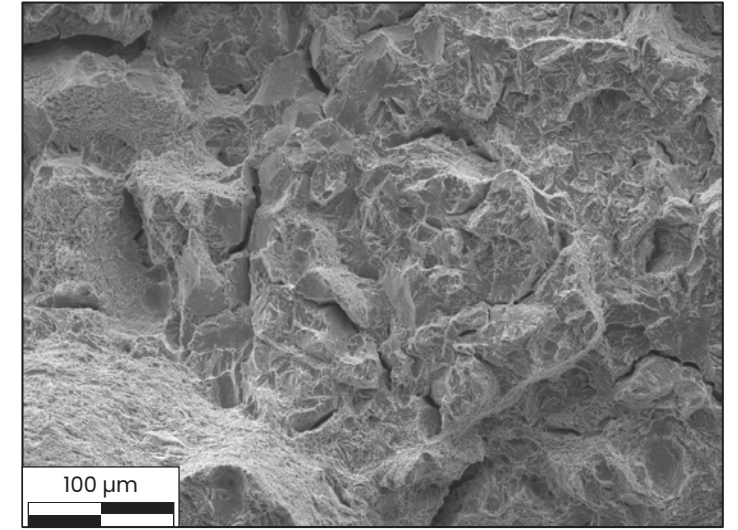
Non-segregated



Moderate macrosegregation



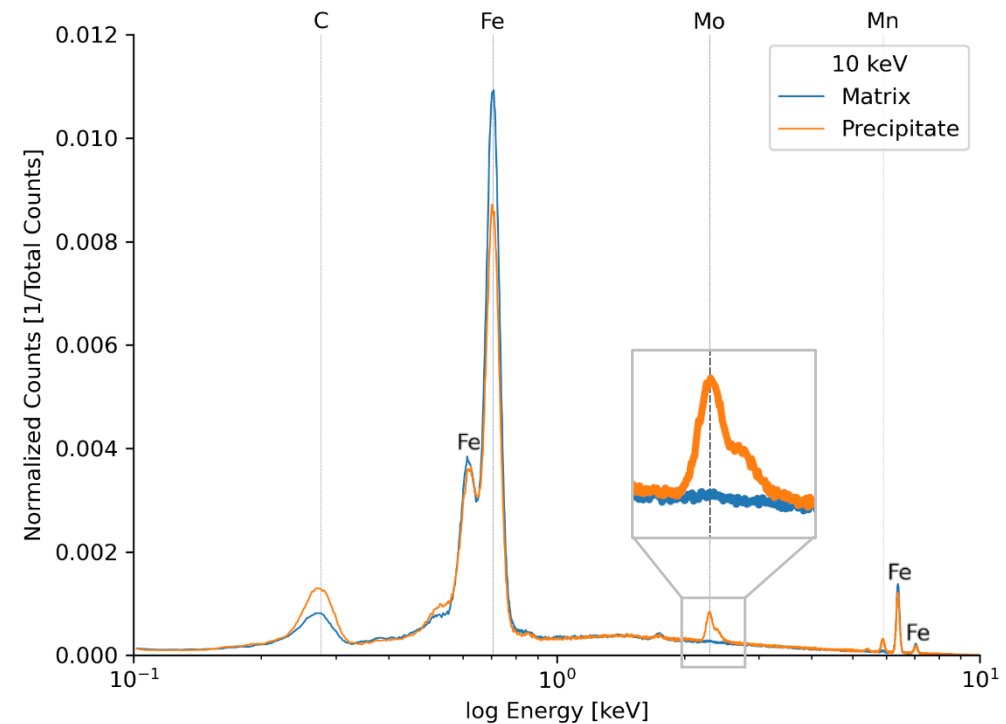
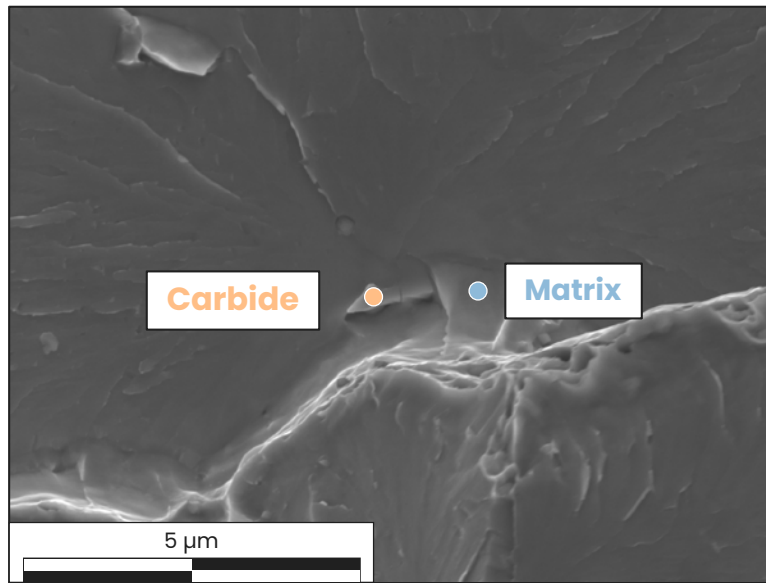
Intense macrosegregation



Initiation sites

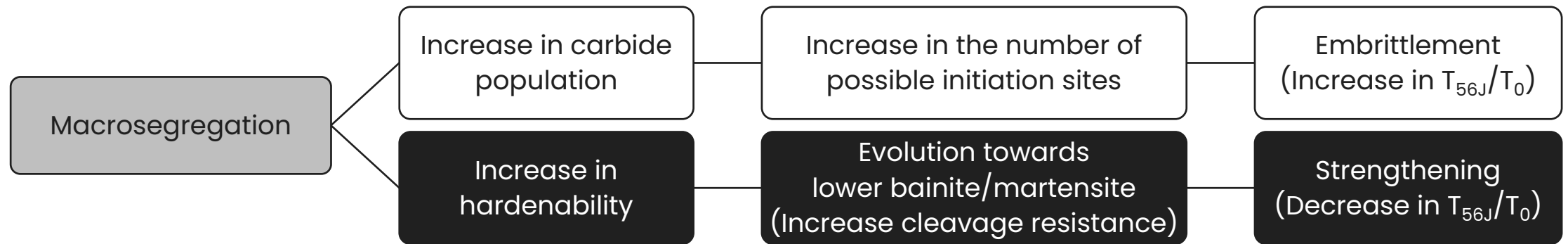
- Determination possible only for **non-segregated** and **moderately macrosegregation**
- Carbides are the dominant microstructural feature at the origin of failure (7/11 cases)
 - Mostly Mo-enriched (5/11)
 - Always found near grain boundaries

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

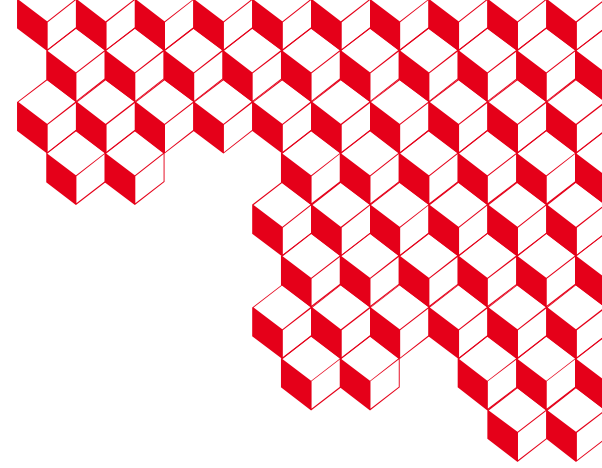
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Cainã BEMFICA

ISAS/DRMP/SRMA/LC2M
Centre de Saclay, Bat. 455 Pièce 102
Gif-sur-Yvette, France

caina.bemficadebarros@cea.fr
Phone : + 33 01 69 08 99 51



Thank you !

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Hinkley Point C reactor pressure vessel, © EDF Energy

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