Carbon Macrosegregation in Large Forgings

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29th Regulatory Information Conference
Rockville, MD
March 16, 2017

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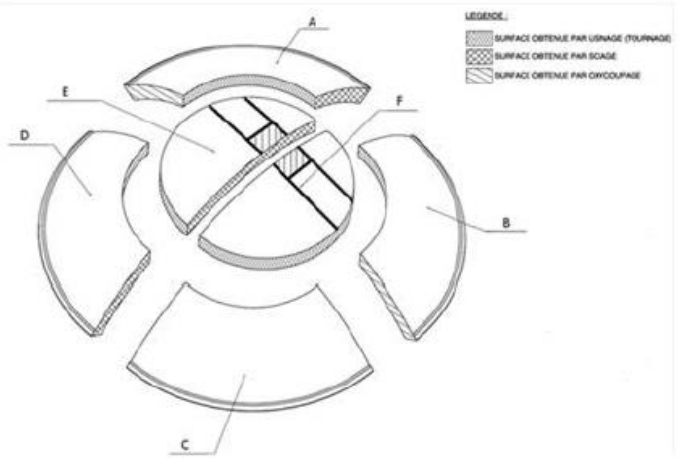
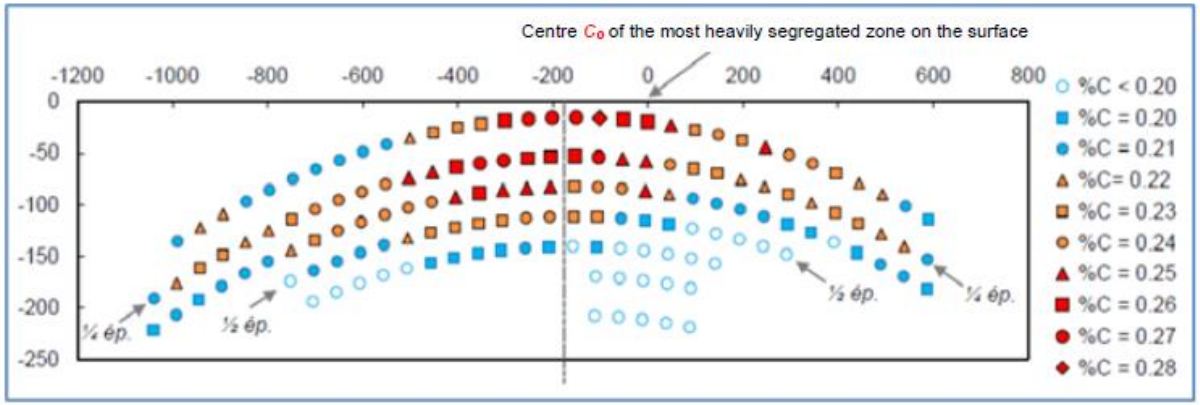
Background – Origin of Carbon Issue

- To qualify the Flamanville 3 EPR head, impact tests were conducted on specimens from surrogate head
- Average absorbed energy was 52 J, below minimum requirement (60 J at 0°C)
- An investigation was conducted to determine cause of low toughness
  - Carbon (C) measurements at outer surface using portable spectrometry revealed large area of positive macrosegregation (high carbon)
- Relevant limits on carbon
  - French limit (16 MND 5): 0.22 wt.%
  - A 508 Cl 2 limit: 0.27 wt.% C
  - A 508 Cl 3 limit: 0.25 wt.% C

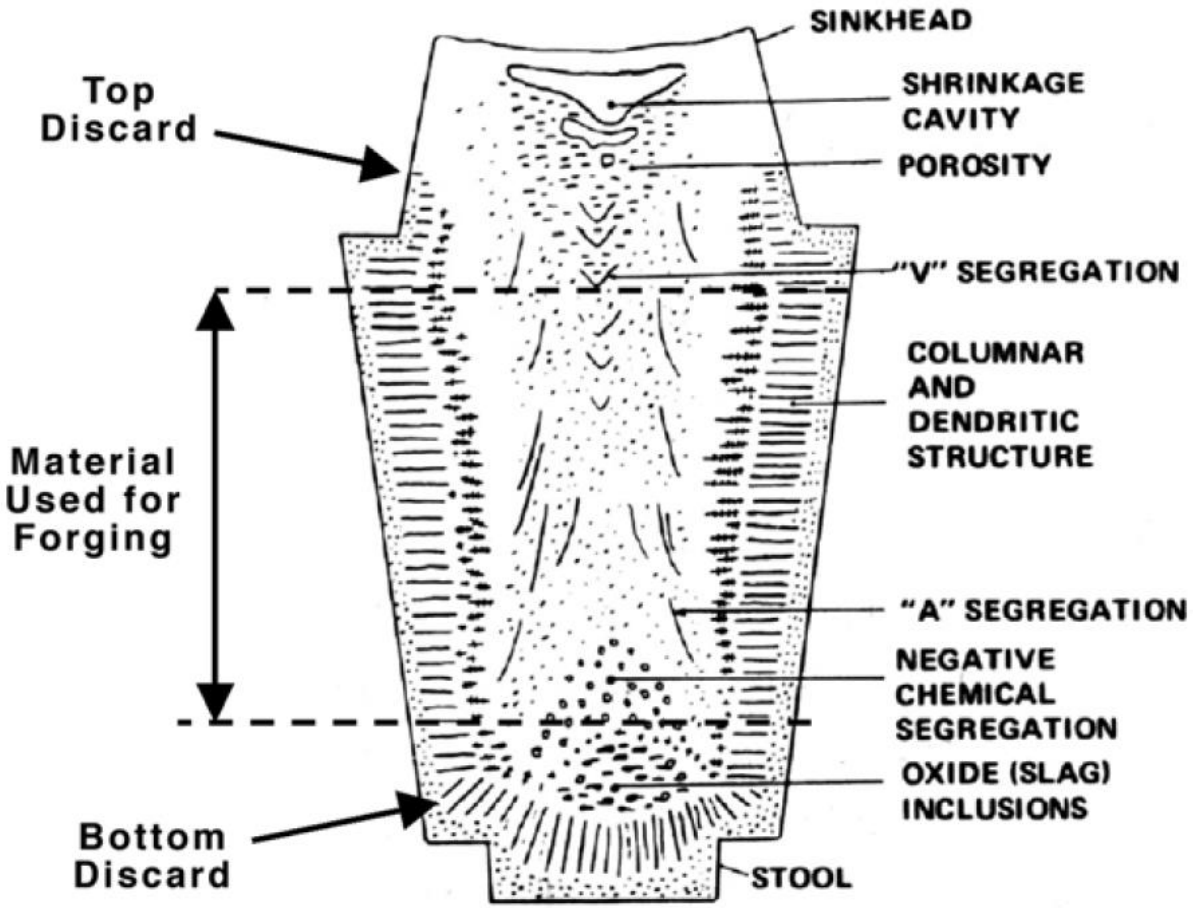




Map of carbon content in similar head;
Figure from CODEP-DEP-2015-037971

Background: What is Macrosegregation?

- Macrosegregation refers to the segregation of alloying elements in an ingot over large length scales (cm or m)
- Macrosegregation occurs during solidification of an ingot
  - Interdendritic fluid flow in the mushy zone, “thermosolutal convection”
  - Sedimentation of solute-poor equiaxed grains from the melt
- Carbon segregation is positive at the top of the ingot and negative at the bottom
- Phenomenon has been recognized and studied for many years – e.g., 9 reports 1926-1940 from the Heterogeneity of Steel Ingots Sub-Committee of Iron and Steel Institute (U.K.)



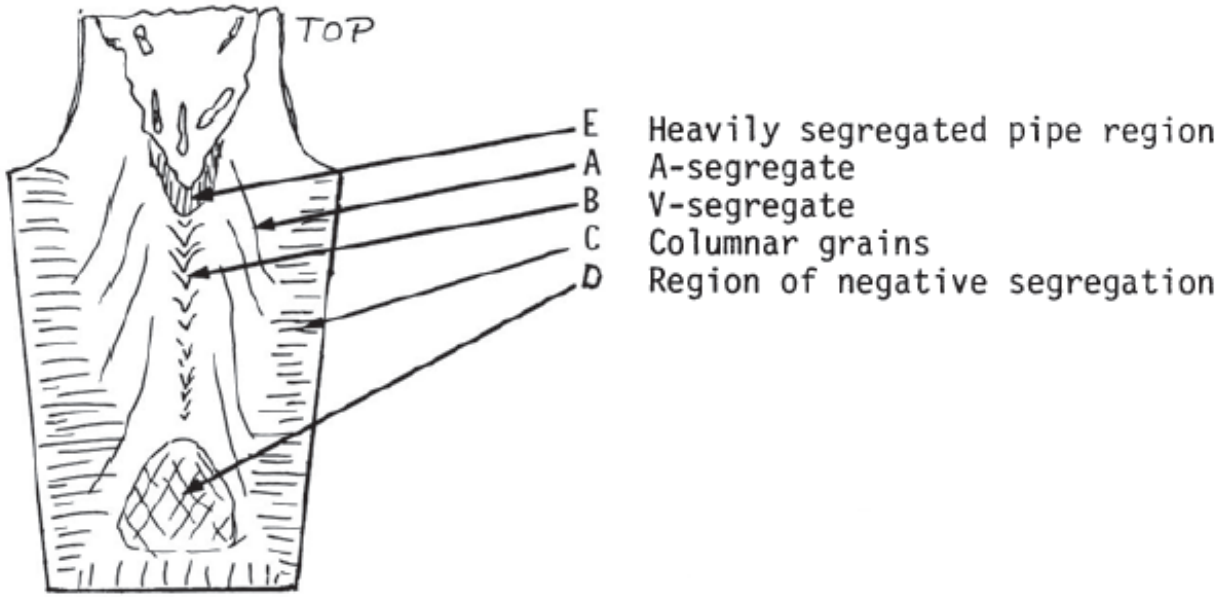
Controls to Minimize Macrosegregation in Ingots

- Carbon macrosegregation is characteristic in conventional ingots and tends to increase with ingot size
- ASTM standard for A 508 requires that “Sufficient discard shall be made from each ingot to secure freedom from piping and excessive segregation.”
  - “Excessive segregation” is not defined
- Specification A 508 imposes several more stringent requirements than ASTM A788 (Steel Forgings, General Requirements):
  - Steel must be vacuum degassed
  - Forgings must be quenched & tempered
  - Large forgings require testing at both ends; and at each end, 180° apart
  - In addition to the ladle analysis, a product analysis is required for the forging
  - Permissible variations in carbon allowed by A788 are not allowed by A 508

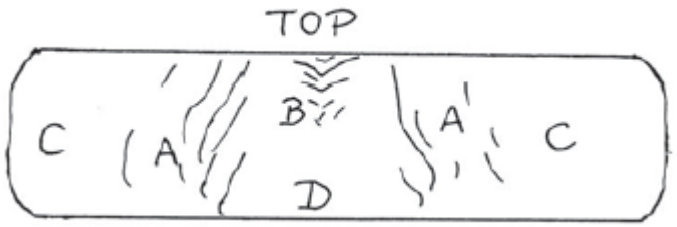
Efforts to Minimize Macrosegregation in Forged Components

- As industrial demand for larger forged components has increased, the size of ingots has increased – and with it, the potential for macrosegregation
- Recognizing the issue and seeking to develop more homogenous ingots, fabricators have developed methods to minimize segregation
  - Japan Steel Works (JSW) multiple pouring method
    - PVP2004-3056: "JSW applies a multiple pouring method in which carbon content is differentiated in each heat for an ingot over 140 ton to minimize carbon segregation in large-sized ingot."
  - Creusot Forge "LSD" ingot design (*Lingot à Solidification Dirigée*)
    - See *"Application of New Types of Ingots to the Manufacturing of Heavy Pressure Vessel Forgings"* by Pierre Bocquet *et.al*., ASTM STP 903, 1986.
- The degree of carbon segregation in any particular component will depend on
  - measures taken by the steelmaker to minimize segregation in the ingot
  - amount of top discard
  - thermo-mechanical path taken to forge the component
- Only a limited volume of the entire component is affected

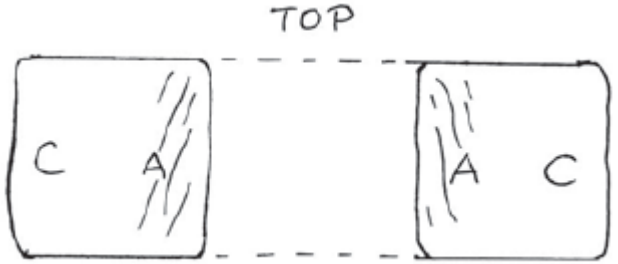
Location of Macrosegregation in the Final Component Depends on Component Shape and How It Is Forged



Figures from
"Macroscopic Segregation in Ingots and Its Implications in Modelling of Structures Made From Heavy Sections" by S.F. Pugh, U.K. Atomic Energy Authority, 1982



Upset disk, such as might be used for fabrication of a head



Forged ring; the center is removed (trepanned), significantly reducing the volume of macrosegregation

Effects of Macrosegregation and High Carbon

- Macrosegregation can cause heterogeneity in a forging
- As carbon is increased, strength increases but toughness decreases
- Limited quantitative data exist on effects of high carbon on the properties of low alloy steels
- Available data in literature suggest that increasing C by 0.1 wt.% increases RT_{NDT} by ~32-35°C (~63°F)
- Higher shift values (e.g., 70°C for 0.3 wt.% C) have been used in France for structural integrity evaluations
- A need exists for additional data on the effect on toughness, to reduce unnecessary conservatisms

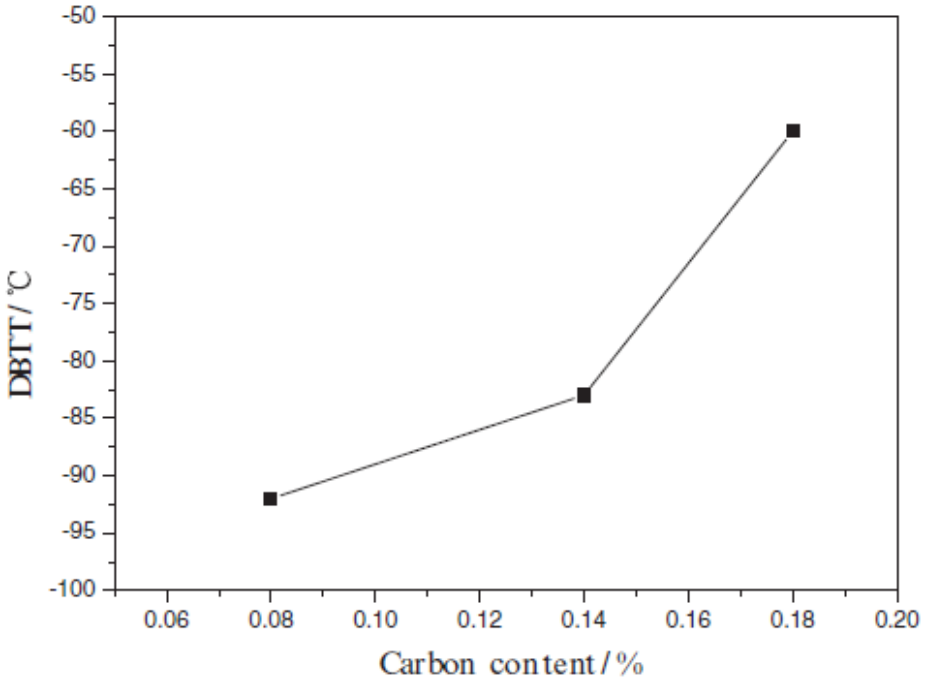


Figure from: "The Influence of Carbon Content and Cooling Rate on the Toughness of Mn-Mo-Ni Low-Alloy Steels" by H. Liu and H. Zhang.

Carbon Macrosegregation in Shell Forgings (1/2)

- Macrosegregation in shell ring forgings is much less than heads because the center of ingot (area of highest segregation) is removed
- Extensive testing and characterization of shell rings with areas of macrosegregation were performed for assessment of the Doel 3 / Tihange 2 RPV hydrogen flaking issue
  - Gérard, R., De Smet, M., and Chaouadi, R., *Material Properties of Reactor Pressure Vessel Shells Affected By Hydrogen Flaking*, PVP2016-63901.
- Conclusions:
  - "There is no effect of the macro-segregation on fracture toughness in non-irradiated or irradiated condition.
  - No effect of the ghost lines on fracture toughness was identified." ['Ghost lines' are areas of microsegregation within the macrosegregated areas]
  - "The effect of a possible higher irradiation embrittlement sensitivity of the macro-segregated zone due to the enhanced contents in Cu, Ni and P was not confirmed by the experiments"

Carbon Macrosegregation in Shell Forgings (2/2)

- EDF/AREVA “Large Forging” Program also studied effects of shell forging macrosegregation
  - Saillet, S. et. al., “*Impact of Large Forging Macrosegregations on the Reactor Pressure Vessel Surveillance Program (PVSP)*”, presentation at Fontevraud 6, 2006.
- Although focus was on surveillance program, influence of macrosegregation on toughness of core shells was also investigated
  - From shell with up to +20% macrosegregation, 72 Compact Tension (CT) (0.5T) specimens were machined and tested at -100 °C (≈ 100 MPa$\sqrt{m}$)
  - Results:
    - No notable change of toughness through thickness
    - Slight increase of toughness near inner surface due to quenching

Conclusions

- Carbon macrosegregation is a long-studied phenomenon that is common in large conventional ingots
- Macrosegregation can be mitigated by various steelmaking controls and processes
- High carbon due to excessive macrosegregation increases strength but reduces toughness of a material
- Several studies have shown no detrimental levels in large reactor vessel shell forgings
- Industry has committed to further study the issue of macrosegregation

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