Solidification of low-alloy steels in heavy ingots:
experimental study of the peritectic reaction by in-situ synchrotron radiography

PhD position – CIFRE – FRAMATOME – IM2NP (Aix-Marseille University)

Industrial context

The segregation of chemical elements in large component made of low-alloy steel, such as the reactor pressure vessel of nuclear power plants, can lead to undesirable local variations in mechanical properties. The segregation occurs during the solidification of heavy ingots and persists through forging and heat treatment operations. To mitigate this phenomenon in components, it is therefore essential to control the solidification conditions of the ingots.

In heavy ingots, chemical segregation occurs on three spatial scales:

- Macrosegregation is observed at the scale of the ingot (~1 m, see Figure 1). It typically refers to the accumulation of solutes such as carbon at the top of the ingot.
- Mesosegregation is observed at the scale of austenitic grains (~1 cm). It indicates the local presence of solute-rich "liquid pockets" between equiaxed grains.
- Microsegregation is observed at the scale of dendrites (~100 µm), which are solidification structures that form during the liquid-to-solid transformation upon cooling. Microsegregation is the core mechanism leading to segregation at all scale in the ingot.

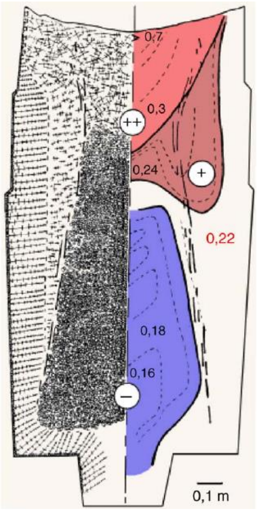

Figure 1 – Macrosegregation in a 65 tons steel ingot [Lesoult et al. 2005].

The solidification of low-alloy steels such as the 18MND5 grade is hyper-peritectic in nature, meaning that solidification starts with the formation of ferrite, followed by a transition to austenite formation until complete solidification. This particular solidification sequence, strongly influenced by the chemical composition of the liquid, has important practical consequences on all segregation scales.

To improve the accuracy of ingot solidification models, it is key to correctly model the various phenomena activated during solidification, and especially the peritectic reaction mentioned earlier. Yet, to this day, reliable experimental data is still missing to enable a satisfactory prediction of segregation patterns in heavy ingots.

PhD objectives

The MCA team of the IM2NP located in Marseille (France), has specialized in the in-situ observation of solidification phenomena by X-Ray radiography at the European synchrotron ESRF. The MCA team has developed a unique unidirectional solidification device named GATSBI (see Figure 2) that allows to study, in real-time, the solidification of steel at temperatures up to 1800°C. In 2025, first proof-of-concept experiments have shown the great potential of this experimental device to collect reliable data on the mushy zone morphology of 18MND5 steel, in representative solidification conditions.

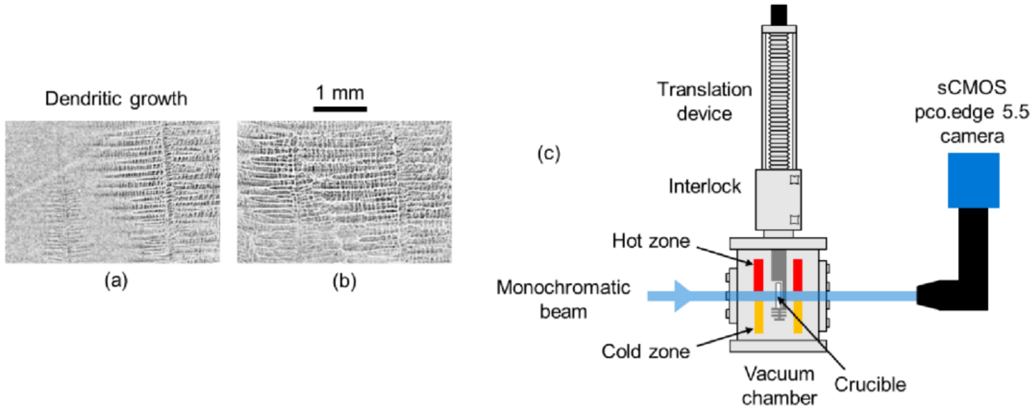

Figure 2 – (a) and (b) Dendritic growth of 18MND5 steel as observed with GaTSBI (c), on the ID19 beam line at ESRF.

In this PhD project, the goal is to systematically characterize the solidification process, especially the peritectic reaction, in various grades of low-alloy steels, depending on local cooling rates and temperature gradients. The objectives include:

- Observing the development of the solidification structure under cooling conditions similar to those in large forging ingots (columnar and equiaxed zones);
- Describing the kinetics of the peritectic reaction;
- Characterizing the morphology of the mushy zone throughout solidification;
- Proposing a model to simulate the formation of the solidification structure.

State-of-the-art experiments will be performed with the GaTSBI setup at the European Synchrotron Radiation Facility located in Grenoble. Ex-situ complementary techniques will also be employed such as micro X-ray fluorescence and SEM-based observations.

Applicant profile

The PhD candidate must hold a master's/engineering degree or equivalent in materials science or physics. He/she should show interest in both experimental and modelling works, along with good writing and communication skills.

Location

The PhD position will be held in Marseille, France, in the Saint-Jérôme site of Aix-Marseille University. Occasional professional travels to Framatome (Lyon) and ESRF (Grenoble) are to be expected.

Contract

3-years CIFRE PhD contract. Expected beginning date: October 2025.

How to apply ?

Please send your CV, a cover letter and your academic transcript from the last two years, to :

- Guillaume REINHART (IM2NP – Aix-Marseille Université); guillaume.reinhart@im2np.fr
- Nathalie MANGELINCK (IM2NP – Aix-Marseille Université); nathalie.mangelinck@im2np.fr
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Recommendation letters are welcomed.