Centre de Mise en Forme des Matériaux

UMR CNRS 7635

PhD Position

Model Order Reduction for Real-Time Digital Twins of Continuous Casting (MORCAST)

Keywords: Continuous Casting, Solidification, Thermomechanical Modeling, Model Order Reduction (MOR), Reduced Basis, Proper Orthogonal Decomposition, hyper-reduction, Digital Twin, Real-Time Simulation,

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Partners of project:

The **MORCAST** project is a CIFRE-funded research project financed by Transvalor, conducted in collaboration with CEMEF (Mines Paris – PSL).

About TRANSVALOR:

TRANSVALOR S.A. is a French software company specializing in the development and commercialization of advanced numerical simulation solutions for material forming and heat treatment processes. Founded in 1984 as a spin-off from CEMEF, TRANSVALOR has established itself as a global leader in simulation software for metalworking industries. The company's flagship products include:

- FORGE®: for hot, warm, and cold forging processes
- THERCAST®: for casting and solidification processes
- DIGIMU®: for microstructure evolution modeling
- COLDFORM®: for sheet metal forming

With over 40 years of expertise, TRANSVALOR serves more than 800 industrial clients worldwide, including major players in automotive, aerospace, energy, and metallurgy sectors. The company maintains strong R&D partnerships with academic institutions and actively contributes to industrial innovation through collaborative projects like MORCAST.

General context of the project:

Numerical simulation of steel continuous casting (CC) is essential to understand complex phenomena such as fluid flow from nozzle, growth of solid shell, stress build up therein, interaction between liquid and solid phases in the mushy zone, contact condition with tools, etc. Nowadays, numerical simulation using software like Thercast® [1] allows predicting the formation of defects such as cracking in the solid shell, solidification cracking in the core of products, central macro segregation, etc, and thus allows optimizing process parameters to avoid or mitigate them. A comprehensive optimization assumes that simulations are fast enough.

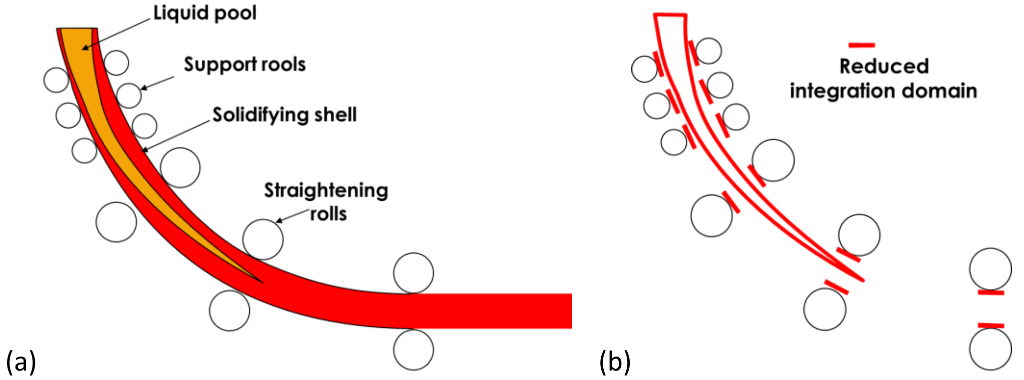

Figure 1. Slice model of secondary cooling zone for thermomechanical modeling: a) full order calculation, b) hyper reduced order model by building the reduced integration domain (RID) with concatenating meshes

PhD objectives:

The **MORCAST** PhD project aims to develop and validate **projection-based reduced-order models** for **continuous casting**, enabling near real-time process prediction, control, and optimization.

Working Environment:

This PhD position offers a unique opportunity to work in a dual environment, combining academic excellence with industrial innovation:

At CEMEF (Primary Location):

You will join CEMEF, the largest research center of Mines Paris – PSL associated with the CNRS. For more than fifty years, CEMEF has been conducting cutting-edge research in mechanics, materials, numerical simulation, and artificial intelligence. The center hosts around 170 people, including approximately 75 PhD candidates, within a highly international and multidisciplinary environment. Located in Sophia Antipolis, Europe's leading technology park, CEMEF offers:

- State-of-the-art computational facilities and high-performance computing clusters
- Access to experimental platforms for material characterization
- Regular seminars, workshops, and international conferences
- Collaboration opportunities with world-renowned researchers

At TRANSVALOR (Industrial Collaboration):

As part of the CIFRE framework, you will have regular interactions with TRANSVALOR's R&D team, providing:

- Direct exposure to industrial challenges and real-world applications
- Access to industrial simulation software and development tools

- Mentorship from experienced software engineers and simulation experts
- Opportunity to see your research integrated into commercial software used globally
- Professional network development within the metallurgy and manufacturing industries

The doctoral project will be supervised by scientists from CEMEF's research teams 2MS and CSM:

- 2MS team: focuses on high-fidelity modeling of the CC process and Inherent strain rate method
- CSM team: focuses on the implementation of model order reduction in the CC process

Profile sought:

- Master's degree (MSc or equivalent) in Computational Mechanics, Applied Mathematics, or Materials Science
- Strong background in numerical simulation (FEM/CFD) and programming (C++, Fortran, Python)
- Interest in model reduction, machine learning, and industrial applications
- Good communication skills and motivation for interdisciplinary work.

The Key point of the subject:

The study is focused on thermomechanical simulations in secondary cooling of steel continuous casting, which are frequently operated by R&D Departments of steel companies, and remain extremely costly in terms of computational time. Such a simulation, often called "slice type" (Fig. 1 a)), consists in conveying a portion of steel slab or billet through the secondary cooling, from the top, close to the mould exit, to the end of secondary cooling after full solidification. More precisely, the portion of the slab or billet is defined by its transverse section (rectangular for a slab) and by a finite length in the casting direction (typically one to two meter long). Its initial shape, possibly curved, complies with the machine configuration (position of support rolls) and its initial state (temperature, solid fraction defining the internal mushy zone) is defined according to upstream simulations of the primary cooling zone. The transient simulation couples heat transfer, mechanics, and possibly transport of chemical species under specific boundary conditions: the lower face has an imposed normal velocity which is the nominal casting velocity; the upper face has an imposed normal stress which is the nominal ferrostatic pressure, variable during the conveying process; these upper and lower faces have zero flux in terms of energy and chemical species. The lateral faces are submitted to specific heat transfer boundary conditions expressing spray cooling while the mechanical contact with the support rolls is expressed by a penalty formulation.

In such coupled simulations the main computational demand is by far from the non-linear mechanical resolution. This is why the present project is focused on the mechanical solver of Thercast®. The optimization of the computation time of the non-linear mechanical resolution will be addressed in two main directions:

1. Application of the Inherent Strain Rate method (ISR). This method has been successfully developed by the proposers of the present project for numerical simulation of additive manufacturing [2]. It consists in proceeding in two steps within the thermomechanical resolution: i) linearization of the non-linear (elastic-viscoplastic) behavior by use of a guessed generalized strain rate, deduced from previous time steps. ii) resolution of the linearized problem by solving a single global set of equations

(avoiding iterative Newton-Raphson iterations), and iii) local corrections in each finite element to account for the effective non-linearity of the behavior law. This strategy proved very efficient when simulating DED additive manufacturing (same results as the reference, speed-up 5.5). In the context of steel continuous casting, the speed-up might be lower, due to contact non-linearity, but could remain significant.

2. Beyond the application of the ISR method, which remains a full-order method, the project will focus on the extension of reduced-order modeling (ROM) to Continuous Casting, along with two axes:

- a Proper Orthogonal Decomposition (POD) based reduced-order modeling (ROM) framework for the thermomechanical behavior of the solidifying shell in continuous casting in the secondary cooling zone (Fig. 1a).
- a hybrid hyper-reduced order model [3], using a reduced integration domain (RID) that includes the semi-solid zone and local roller contact zones where a local finite element approximation is coupled to a reduced basis. (Fig. 1b)

Our expertise in implementing ISR and ROM methods for other processes and software will directly benefit their implementation and adaptation to continuous casting. The different approaches, possibly combined, will be developed, coded in Thercast® software, and evaluated on slice type simulation cases, representative of the current practice of R&D industrial centers. The objective is to demonstrate the potential of the methods, up to the development of digital twins for CC secondary cooling.

Bibliography references:

[1] R. Forestier, F. Costes, O. Jaouen, M. Bellet, Finite element thermomechanical simulation of steel continuous casting, in: Proceedings MCWASP XII, 12th International Conference on Modeling of Casting, Welding and Advanced Solidification Processes, Vol. 12, The Minerals, Metals & Materials Society, Warrendale, Pennsylvania, USA, (2009), 295-302.

[2] M. Bellet, J. Keumo Tematio and Y. Zhang. The inherent strain rate method for thermo-mechanical simulation of directed energy deposition additive manufacturing. International Journal for Numerical Methods in Engineering, 124(2023) (18), 4058–4074. https://doi.org/10.1002/nme.7293.

[3] Fauque J, Ramière I, Ryckelynck D. Hybrid hyper-reduced modeling for contact mechanics problems. Int J Numer Methods Eng. 2018; 115: 117–139. https://doi.org/10.1002/nme.5798, hal-01853252v1.

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https://applyfor.cemef.mines-paristech.fr/phd
Application deadline :
30/06/2026</td></tr>
<tr><td>Working time</td><td>Full time</td></tr>
<tr><td>Duration</td><td>3 years</td></tr>
<tr><td>Salary</td><td>Approximately 31.8 k€ gross per year (before income tax)</td></tr>
<tr><td>Location</td><td>• Transvalor SA – 950 avenue Roumanille – 06410 BIOT
• CEMEF Mines Paris, 1 rue Claude Daunesse, 06904 Sophia Antipolis, France</td></tr>
<tr><td>Starting date</td><td>Oct. 1st, 26</td></tr>
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