

Modelling the vertical spincasting of large bimetallic rolling mill rolls

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ABSTRACT: In order to take into account the dynamic effects of molten metal during solidification, a methodology is presented to interface a metal solidification solver with a specifically developed flow dynamics solver.

Keywords: Hot rolling mill roll, fluid mechanics, metallurgy, solid mechanics, projection method, conservative level set method, semi high speed steel, metal solidification, dynamic effects, spincasting.

1 INTRODUCTION

The aim of this project is to provide a numerical solution for simulating the centrifugal casting of large bimetallic rolling mill rolls. These products are made up of two different materials: a spherical graphite iron as core material, and a highly resistant steel as outer material. Both materials are sequentially poured into a spinning mould, the outer material being poured first. In 1970, the Belgian manufacturer Marichal Ketin adapted the vertical spincasting process to bimetallic hot rolling mill rolls manufacturing (see **Fig 1**). Since then, this technology has been successfully used, with empirical developments and adjustments.

However, the recent introduction of semi high speed steel (semi HSS) as outer material leads to unpredictable defects, weakening the whole structure of the product. The nature of this casting technique leads to a need for numerical simulation: due to high rotation speed and temperature, visual observation is said to be impossible and sensors use is very restricted. In order to overcome the computational cost of the simulation, a fluid solver and a solid solver are coupled, and a two dimensional approach is used, despite its physical shortcomings.

2 Global methodology

The strategy for the developments of this project mainly falls into three categories:

- Building a finite volume method (FVM) fluid solver with complex abilities;
- Characterizing the material parameters that will be used with the finite element method (FEM) thermal mechanical metallurgical simulation;
- Interfacing both the FVM fluid solver and the FEM solid solver.

As a result of on-going research, a two dimensional fluid solver is being developed using the popular projection method. Regarding free surface tracking, the level set method has been preferred. Following the spirit of the previous developments by the applied hydraulics team, a conservative formulation of level set is used^{5,6}. Actually, code developments include dealing with the issues raised by such a formulation, and the validation based on classical test cases. Another fundamental part of the project is material characterization, required by both fluid

and solid solvers. This is fundamental to the solidification simulation. The metallurgical solver requires material parameters to be characterized for each solid phase, and this is often very difficult to achieve in practice.

The basic assumption of the project is that the fluid simulations will keep on running until the whole liquid metal becomes solid. Three distinct areas are defined: the solid, the liquid and the mushy zones. In the liquid zone, constant physical parameters might be assumed, and liquid metal assumptions are used. In the solid zone, the FEM thermal mechanical solver^{1,2} is used. The mushy zone is determinant: here, the physical parameters evolve and lead to solidification, it is also less geometrically and temporally steady than the two other domains. Given an ad-hoc time scale analysis, informations between both simulations are exchanged. In order to avoid the occurrence of too many convergence problems simultaneously, interfacing is done in two steps: the first one neglecting the large complexity of some metallurgical phenomena, and the second one taking them into account (see **Fig 2**). A major issue when trying to numerically simulate the vertical spincasting of large hot rolling mill rolls is the extend of the geometrical domain. A three-dimensional model fully integrating fluid and solid equations is reasonably out of reach, at least with a mesh characteristic size sufficient for predicting the apparition of tiny cracks in the structure of the roll.

3 Solidification modelling

3.1 Thermal mechanical metallurgical solver

The solid model is implemented in the LAGAMINE non-linear finite element code, which has been developed in house^{1,2} by the ArGENCO department since the early eighties. As it is dedicated to solid mechanics modelling, Lagamine has been written in updated material (Lagrangian) formalism. No fluid flow is thus modelled: molten steel is only present in the model to provide matter to solidify and apply ferrostatic pressure. The modelling of the thermal metallurgical analysis uses an original differential formulation of the diffusive transformation model and the Koistinen Marburger⁴ law for martensitic transformation. The metallurgical model is based on time temperature transformation (TTT) diagrams and assumes the validity of the additivity principle in order to simulate the diffusive phase transformations during any given thermal history. Due to the evolving chemical composition of the semi HSS matrix during cooling, the initial TTT diagram cannot be expressed through the means of a Kirkaldy-like³ method. However, inverse analysis of available continuous cooling transformation (CCT) diagrams directs the research team when defining the input. The model computes for each integration point the thermal flows, stress tensors, and percentages of presence for each solid phase: austenite, ferrite, perlite, bainite and martensite. The model can take into account numerous couplings, as shown on **Fig 2**. At first, a simplified approach is used, substituting the costly computation of exact metallurgical states by a trivial approach where a variable dilatation coefficient will account for phase transformations. The full model will be used at first in order to adjust the thermal dependence of this coefficient. This solidification model has been extensively compared and validated^{1,2}. The mechanical behaviour is implemented using a thermal elastic plastic law.

3.2 Material parameters characterisation

The range of parameters to characterize is quite wide, and can be split into two parts: the thermal physical parameters, and the thermal mechanical parameters. The first group includes, for each solid phase: density, thermal conductivity, specific heat, linear thermal expansion

coefficient. For each phase transformation: latent heat and strain of transformation. Furthermore, viscosity as a function of temperature, and eventually the heat transfer coefficients of the mould with its surroundings are needed. Amongst the second group, for each solid phase: Young's modulus, Poisson's ratio, yield stress and hardening parameter. Eventually, the big part of this second characterization would be the establishment of the TTT diagram for our steel. Last but not least, the stress effect on each phase transformation has to be expressed. The studied hot rolling mill rolls are constituted by two fundamentally different materials: spherical graphite iron in the core, and semi high speed steel in the shell. These have totally different mechanical and physical behaviour, so parameters characterization has to be performed for both alloys. The parameters characterization started¹⁰ with a 6 month experimental campaign in Padova University, where a *Gleeble system* and a *material testing system* (MTS) have been used for mechanical characterization under high temperature loading. Experimental testing will carry on in parallel with the numerical developments. Current tests include *differential thermal analysis* (DTA), *differential scanning calorimetry* (DSC) and *cryogenic quenching*.

4 Molten metal dynamic modelling

The solver used to model the liquid is called WOLF2DV. This solver is a part of a hydrodynamic modelling system developed for about ten years within the unit of Hydrology, Applied Hydrodynamics and Hydraulic Constructions of the University of Liege. This solver is based on the technique of the finite volumes applied on a structured grid. Time integration is ensured by the well known Runge-Kutta schemes.

4.1 Solving the Navier-Stokes equations: the projection method

In order to model the liquid phase of molten metal, which viscosity and density are experimentally characterized (see sub-section 3.2), the Navier-Stokes equations are solved in the vertical plane of the flow. Several resolution methods can be applied such as the implicit method, the method of pseudo-compressibility but also the projection method⁷ that was in this case selected. It consists into separating the resolution of the equations into two steps. The first one is called the *transport* step while the second one is the *projection* step. The transport step consists in neglecting the pressure gradient and keeping only the two velocity unknowns. The resolution of the two equations of momentum balance provides a first approximate velocity field, which is not divergence free. Next, the projection step consists in restoring the incompressibility of the velocity field by resolving a Poisson's equation on the pressure with a source term corresponding to the divergence of the approximate velocity field. This step enables to determine the new field of pressure at next time step but also provides the corrections that must be applied to the velocity field to obtain the final field with zero divergence. The validity of this solver was checked on many benchmarks including, for instance, the backward facing step flow⁸, as shown on **Fig 3** and **Fig 4**.

4.2 Free surface tracking: the level set method

The solver described above enables the computation of pressurized flows. In contrast, the practical problem of interest, vertical spincasting, involves an interface between the liquid and the air. It is consequently necessary to conceive a process enabling to track the free surface of the flow. Among the many methods existing in the literature, the level set⁹ method was selected. This method has been often applied in various fields such as medical imagery, or

flames front propagation. The application within the framework of liquids is not very widespread yet, but seems promising. The level set method has an advantage: it follows any movement of an interface by means of a simple convection equation. Suitable numerical schemes must however be implemented to correctly discretize this equation in the case of important curvature. In addition, the level set concept requires a velocity field to be expressed in the whole computational domain (both molten metal and air). However, the projection method is run in the liquid domain only, due to CPU time requirements. Consequently, an original method has been developed to define a velocity field located in a virtual fluid standing for the air.

4.3 Boundary conditions

In addition to the boundary conditions placed on the fixed edges (velocity, pressure...), the management of free surface inevitably requires the imposition of an additional boundary condition, consisting in prescribing the atmospheric pressure at the moving interface.

Computation cells are considered as completely filled or completely empty but no intermediate situation is accounted for (discontinuous approach of the calculated field). On the opposite, the pressure boundary condition on the free surface is imposed in a continuous way at each time step.

4 Conclusions

The next steps of this project are the completion of the level set solver, the fine tuning of the alloy thermal physical mechanical parameters, and the interfacing of the fluid and solid solvers.

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Figures and Figure Captions:

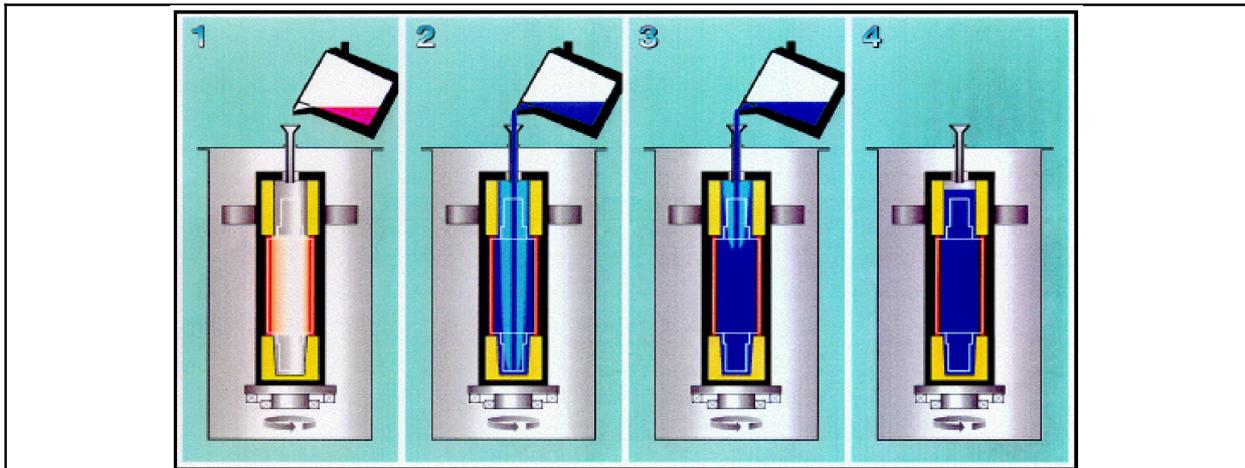


Figure 1: *The vertical spincasting process*

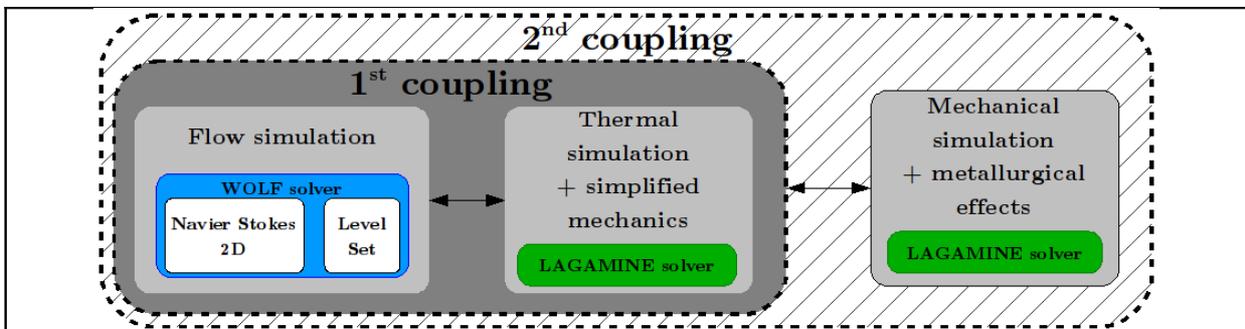


Figure 2: *Global interfacing strategy*

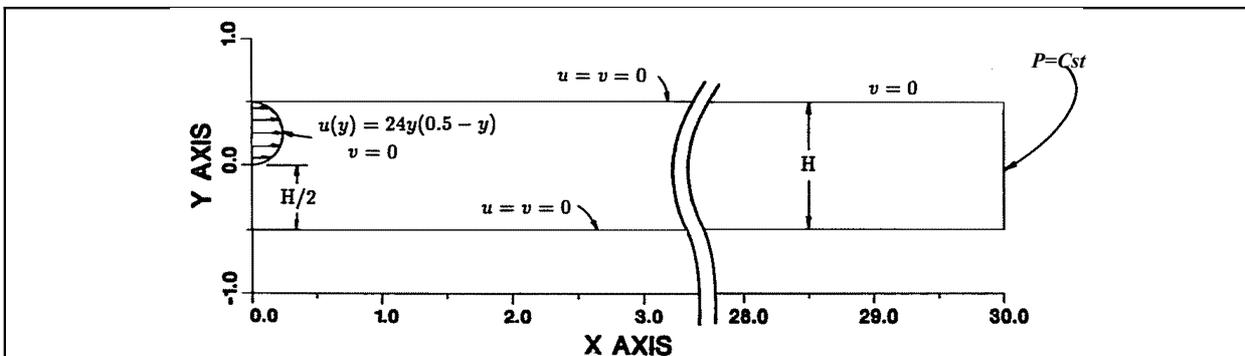


Figure 3: *Geometry of the benchmark and prescribed boundary conditions*

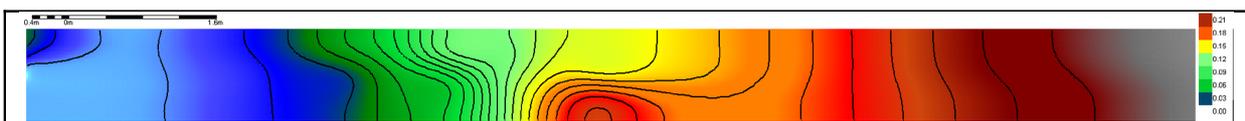


Figure 4: *Field of pressure with curves of iso-pressure*