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MODELLING THE VERTICAL CENTRIFUGAL CASTING OF LARGE BIMETALLIC ROLLING MILLS

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Abstract. In order to take into account the dynamical effects of molten metal during solidification, we want to interface a metal solidification solver with a flow dynamics solver.

1 MANUFACTURING PROBLEM

The aim of this project is to provide a simulation solution for centrifugal casting of large bimetallic rolling mills. These products are made up with two different steel alloys: a graphite iron as core material, and a highly resistant steel as outside material. The two materials are sequentially poured into a rotating mould (The outer material beeing poured first). In 1970, Marichal Ketin adapted the vertical spin casting process to rolling mills manufacturing (see figure 1). Since then, this technology has been succesfully used, with empirical developments and adjustments. However, the recent introduction of semi high speed steel (high chromium and manganese) as the outside material has led 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.

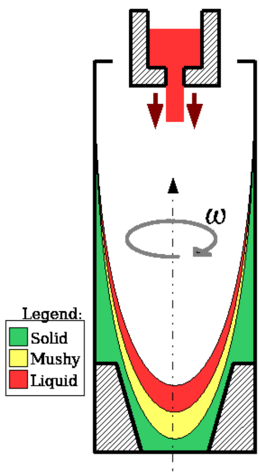

Figure 1: centrifugal casting process

2 DEFECTS ANALYSIS

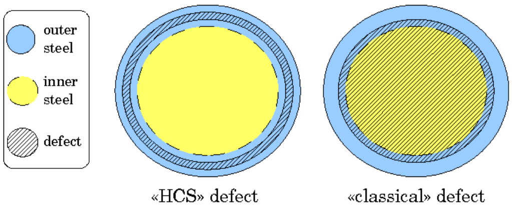

Figure 2: defects classification

Traditionnaly, mechanical defects are appearing on the cylinder during heat treatment, this is a well known phenomena which happens when the strain between the outside steel and the core material is to high, thus leading to an internal ring inside the cylinder collapsing. The kind of defects that we are interested in is much different, it is made up of tiny cracks appearing all along the circumference of the outside material (see figure 2). The consequence of this external ring of defects is the cylinder rupture in the worse case, or a seriously shortened product life range in the better case.

3 SIMULATION

The following steps have to be realized, as far as numerical developments are concerned:

- Build a generic fluid solver that takes into account the fluid's free surface[1], (surface tension) the energy balance (thermal effects) and variable physical parameters.
- Interface this dynamic solver with an existing static themometallurgical finite element solver[2] that has been successfully used in the field of continuous casting.

3.1 Fluid Equations

We are using the Navier Stokes equations, with variable viscosity and thermal conductivity. Furthermore, the following assumptions can be made: inviscid flow, (as far as mushy zone is not concerned) turbulent flow, 3D flow. The Prandlt number is very small, thus heat convection can be neglected. We assume Boussinesq approximation. Our equation system can be written as follows (see variables definition § 5):

$$\operatorname{div} \underline{V} = 0 \tag{1}$$

$$\partial_t \underline{V} + (\underline{V} \cdot \underline{\nabla})\, \underline{V} - \operatorname{div}\left(\nu \underline{\nabla \underline{V}}\right) + \underline{\nabla \Pi} = \underline{f} + \underline{B(\theta)} \tag{2}$$

$$\partial_t \theta = \frac{1}{\rho C_v} \triangle \left(\lambda \theta\right) + \dot{q} \tag{3}$$

The tracking of the fluid interface is performed with a Level Set metod[1]:

$$\partial_t \phi + (\underline{V} \cdot \underline{\nabla})\, \phi = 0 \tag{4}$$

$$|\nabla \phi| = 1 \tag{5}$$

$$|\nabla \phi| \cdot |\nabla \underline{V}| = 0 \tag{6}$$

3.2 Fluid numerical resolution

The Navier Stokes system of equations is solved thanks to the projection method. We have implemented several kinds of space and time discretization techniques, in the scheme of finite differences. For instance we have implemented weighted essentially non-oscillatory[1] space discretization, and Adams Bashforth[1] time discretization. A finite volume implementation is in the works. The free shape tracking in its current implementation uses the fast marching method and a first order space discretization. We are planning to express the synergy between conservation equations and free shape evolution by the means of the ghost fluid method[1].

3.3 Interfacing

The basic assumption of the project is that we will keep on running the fluid simulations until the whole liquid metal has been solidificated. Given figure 1, we define three distinct areas: the solid metal, the liquid metal and the mushy zone. Within the liquid zone, we might assume constant physical parameters and use the liquid metal assumptions. Within the solid zone, we run the finite element thermo mechanical solver.

The mushy zone is determinant: in this zone the physical parameters evolve and lead to solidification. This zone is geometrically and temporally less steady than the two others. Given an ad-hoc time scale analysis, we will exchange informations between the two simulations, and let the two domains evolve accordingly.

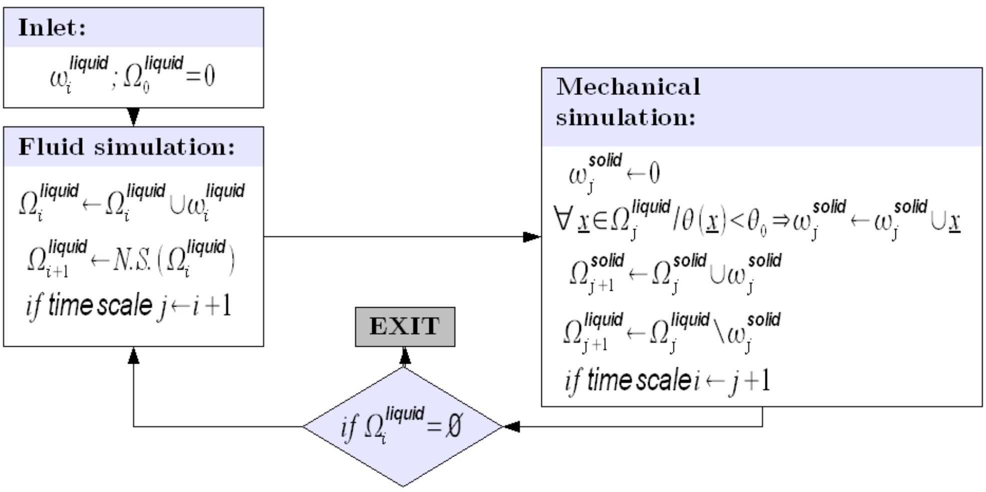

Figure 3: interfacing the simulations

ω_i^{liquid} is the domain attached to the liquid metal poured into the mould at time step i.
Ω_i^{liquid} is the domain occupied by the whole liquid metal at time step i.
ω_i^{solid} is the domain occupied by liquid metal that turns into solid state at time step i.

4 PHYSICAL PARAMETERS

In order to calibrate our numerical models, we need to characterize the physical parameters of the materials involved in the industrial process. The required experiments will be performed both by contractors and during a six month testing campaign at DIMEG, (Dipartimento di Innovazione Meccanica e Gestionale) Padova University, Italia.

4.1 Requirements for fluid simulation

We need to evaluate the following thermophysical parameters: density, thermal conductivity, specific heat, coefficient of linear thermal expansion and viscosity; as functions of the temperature. Most of these can be measured by performing a differential thermal analysis. The case of the viscosity remains problematic and a way to adress it has yet to be found.

4.2 Requirements for thermomechanical simulation

This simulation requires a large amount of parameters to be determined. Amongst them, we can quote setting up the TTT diagrams of the materials, characterizing the behaviour of phase transformations under stress, measuring the strain and enthalpy these transformations produce, finding out about the elastic and plastic properties of each phase. An issue when adressing these measurements is to be able to reproduce the industrial environment within the scale of the testing machine, so that the phase analysis are consistent with the reality of the process.

5 DEFINITIONS

$\underline{V}$ velocity field	ν kinematic viscosity	ρ density
θ temperature	r radial distance	ω angular velocity
$\dot{q}$ heat exchange coefficient	p pressure	C_v specific heat
β volume thermal expansion coefficient	λ thermal conductivity	ϕ level set function
$\Pi = \frac{1}{\rho}(p - \frac{1}{2}r^2\omega^2 - \rho_0 \underline{f} \cdot \underline{x})$	$\underline{B(\theta)} = \beta(\theta - \theta_0)\underline{f}$	$\underline{f}$ body forces

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