IOP Conference Series: Materials
Science and Engineering

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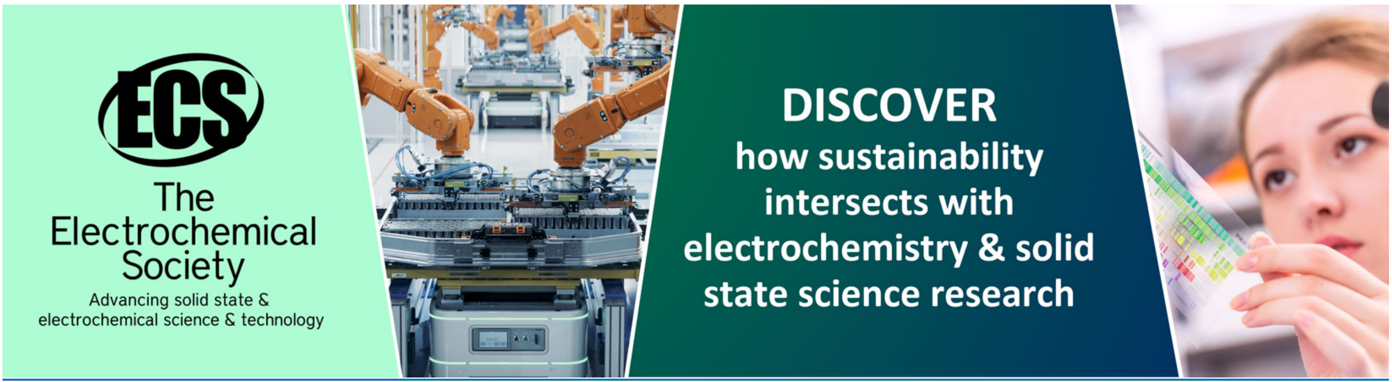
To cite this article: E Kaschnitz 2012 *IOP Conf. Ser.: Mater. Sci. Eng.* **33** 012031



MCWASP XIII IOP Publishing
IOP Conf. Series: Materials Science and Engineering **33** (2012) 012031 doi:10.1088/1757-899X/33/1/012031

Numerical simulation of centrifugal casting of pipes

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Abstract. A numerical simulation model for the horizontal centrifugal pipe casting process was developed with the commercial simulation package Flow3D. It considers - additionally to mass, energy and momentum conservation equations and free surface tracking - the fast radial and slower horizontal movement of the mold. The iron inflow is not steady state but time dependent. Of special importance is the friction between the liquid and the mold in connection with the viscosity and turbulence of the iron. Experiments with the mold at controlled revolution speeds were carried out using a high-speed camera. From these experiments friction coefficients for the description of the interaction between mold and melt were obtained. With the simulation model, the influence of typical process parameters (e.g. melts inflow, mold movement, melt temperature, cooling media) on the wall thickness of the pipes can be studied. The comparison to results of pipes from production shows a good agreement between simulation and reality.

1. Introduction

Ductile iron water pipes and piles for deep foundation engineering are produced using the “de Lavaud” horizontal centrifugal pipe casting technique. In this process, the liquid iron is filled through an open channel into a fast rotating hot-work tool-steel mold that is slightly tilted. The tool-steel is water-cooled at the outside. In order to distribute the metal, the spinning mold including its cooling system is shifted axially in a controlled movement.

The numerical simulation of this process is challenging, no description of its numerical simulation was found in literature. Some papers describe the less complex vertical centrifugal casting process [1-6]. Besides taking into account the mass, energy and momentum conservation equations and the free surface tracking, the following phenomena have to be considered for the horizontal centrifugal casting process of pipes: (i) relatively fast radial movement of the mold; (ii) relatively slow but time dependent movement of the mold in axial direction; (iii) time dependent inflow of the iron along the channel; (iv) friction between the liquid and the mold; (v) turbulence and viscosity of the iron. The situation is hindered by an unfavorable relation between the relatively thin wall thickness of the tube (in the millimeter range) and its overall length (several meters).

After overcoming instability difficulties, it was possible to develop a valid model with Flow3D. In this work, the basic principles of the solution method are discussed; examples of numerical simulations and practical experiments are presented.

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2. Simulation model

The geometry of the model consists of a mold from tool-steel and a closing core from cold-box bonded silica sand, both parts are spinning and moving (figure 1). An open feeding channel is extended into the mold, this channel is fixed. The outer side of the mold is water-cooled (significant heat flow), the inner side contains air (almost no heat loss).

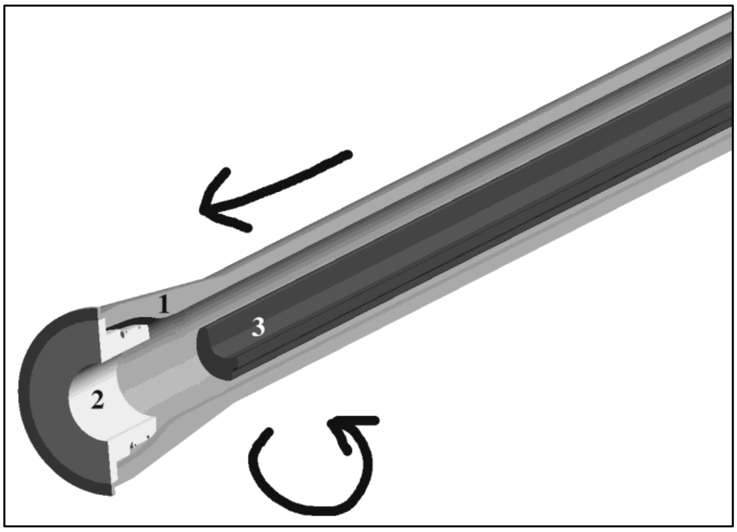

Figure 1. Vertical cut through the geometry of the model (1, mold; 2, sand core; 3, open feeding channel). The arrows show the direction of the movement of mold and core.

The mold and the core (but not the open channel) are cylindrical. As the melt flow follows the inner surface of the mold most of the time, a cylindrical coordinate system was chosen. In comparison to a regular Cartesian coordinate system, most of the unfavorable flow between neighboring cells under an angle of 45 degree is avoided.

For faster and better computations, the (cylindrical) mesh is aligned to the mold that is slightly tilted. This means the gravity vector gets the same tilt in the axial direction and splits in two components. Using the cylindrical mesh, the so-called “Non-inertial-reference-frame”-model of Flow3D has to be introduced to be able to define the gravity vector appropriately [7].

The relatively slow but time dependent movement of the mold is described by the “General-moving-obstacles”-model of Flow3D. This model shifts the assigned obstacles (mold and core) according to the pre-defined motion. Additional source terms according to the loss of mass, momentum and energy are added to the conservation equations at mesh cells in the vicinity of the shifted obstacles to compensate for these cells now covered by the obstacle [7].

This approach is not suitable for the relatively fast spinning of the mold and core, because the time steps become increasingly smaller with increasing spin velocity. Meaningful simulations would take months or years. For the rotational movement of mold and core, the so-called “Ospin”-model of the software package Flow3D was used. This model does not spin the obstacle itself, but transfers an appropriate amount of momentum as shear force from the obstacle in contact with the melt (inner surface of the mold and outer surface of the core) to the melt itself. The simulation model is comparable to a merry-go-round, where the motionless person outside pushes the child in the seat for rotational movement.

The free surface and solidification behavior of the fluid was modeled with Flow3D in a standard way. But Flow3D does no momentum and mass conservation calculations for already solidified cells. For this reason, as soon as the melt in a cell is solidified, the rigid cell is moved artificially by the predefined rotational and horizontal movement. The rotation speed leads only to a limited centrifugal pressure in the melt (the wall-thickness is rather small): the solidification behavior is not assumed to be influenced by the rotation.

The simulated pipes have a wall thickness of approximately five millimeter and are several meter long. This means that even big meshes with long computation times (up to three weeks) are relatively coarse. For that reason, special care has to be taken to choose appropriate values for viscosity and the turbulence model as well as the amount of shear stress that is transferred from mold to melt. A Renormalization-Group method is used for the transport equations for turbulent energy and its dissipation (k-epsilon model). A surface roughness factor provides additional shear stress between wall and the first cell layer of metal. These parameters are slightly dependent on the relatively rough mesh. This dependency should vanish for better meshes, but these are not to compute in reasonable time-spans nowadays. In order to approximate the fluid flow with correct parameters, practical experiments were carried out.

3. Experiments

The experimental setup consists of an electrical engine driving a horizontal cylindrical mold at precisely controlled revolution speed [8]. The control provides either constant speed or an angular velocity ramp at constant acceleration. The mold used for the experiments was a 300 mm piece of an original 5 meter hot-work tool-steel mold with its original inner surface. The sample mold has two lids at the front and at the backside; the front side lid is transparent to be able to watch the fluid inside (figure 2).

Figure 2. Experimental setup for the spinning experiments (1, mold; 2, engine; 3 gear; 4, high-speed camera).

Two different fluids were used for the experiments: colored water at room temperature and Rose's alloy (Bi, 50 wt-%; Pb, 25 wt-%; Sn, 25 wt-%) at approximately 100°C. The behavior of the fluid at different revolution speeds and different acceleration ramps was filmed from the front by a high-speed digital camera at 600 frames per second.

Figure 3 shows the shape of the free surface of the metal at a certain revolution speed. As the contrast of high-speed movies is poor in principle (and even worse in a printed paper), the interface position in the figure is marked by red arrows. The metal undergoes three phases during acceleration: (i) it forms a wedge shaped surface along the cylinder; (ii) the free surface decays and a curtain forms; (iii) when the angular velocity is high enough, the looping condition is satisfied and suddenly the curtain vanishes and the metal turns stable along the inner surface of the mold. This behavior depends mainly on viscosity of the melt and the surface condition of the mold. Figure 4 shows two simulations with different surface roughness, in one case the melt is unstable and forms a curtain, the other case shows a stable spinning of the melt.

In a second experimental setup, the engine and gear system was turned by an angle of 90 degree to use a part of the mold as a turntable. With that setup, liquid cast iron could be used instead of Rose's alloy. Using the gained knowledge from the experiments, meaningful input parameters were found for the simulation of the specific industrial pipes.

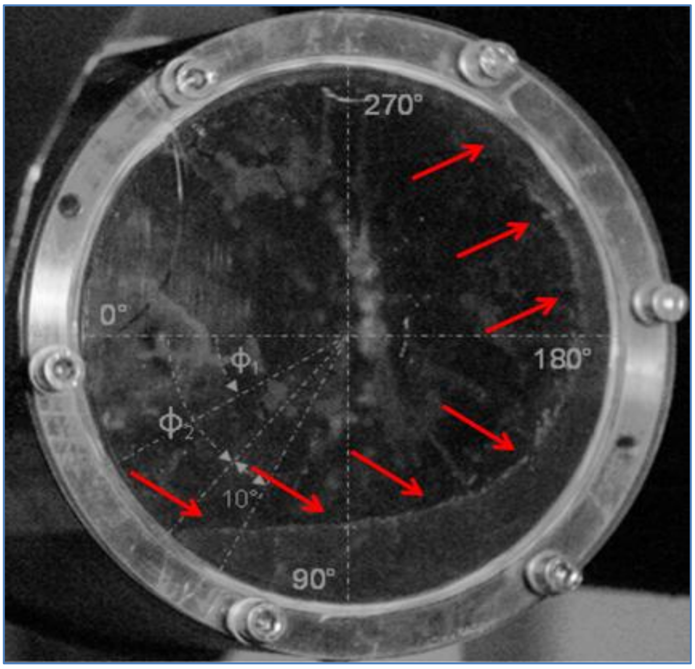

Figure 3. Shape of the free surface of the Rose’s alloy at a selected revolution speed.

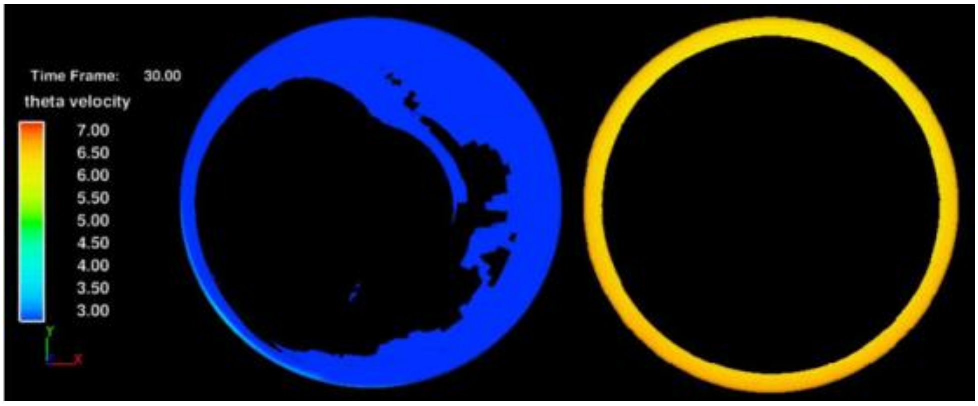

Figure 4. The simulation with low surface roughness (left) shows an unstable melt curtain, the simulation with an appropriate surface roughness (right) shows a stable melt following the looping condition.

4. Results

Figure 5 shows an example of the temperature distribution during filling of a pipe in a front view with mold and core faded out.

The wall-thickness of the produced pipes should be as uniform as possible. Therefore, the most interesting simulation result is the predicted wall-thickness of a pipe along its overall length. From each individual simulation with specific production parameters, the position of each fluid cell, its size and fill fraction was read out from Flow3D in order to compute the wall-thickness along the length. Depending on production parameters, the shape of the pipe can be quite different. As an example, figure 6 shows the wall-thickness of several pipes as a function of length.

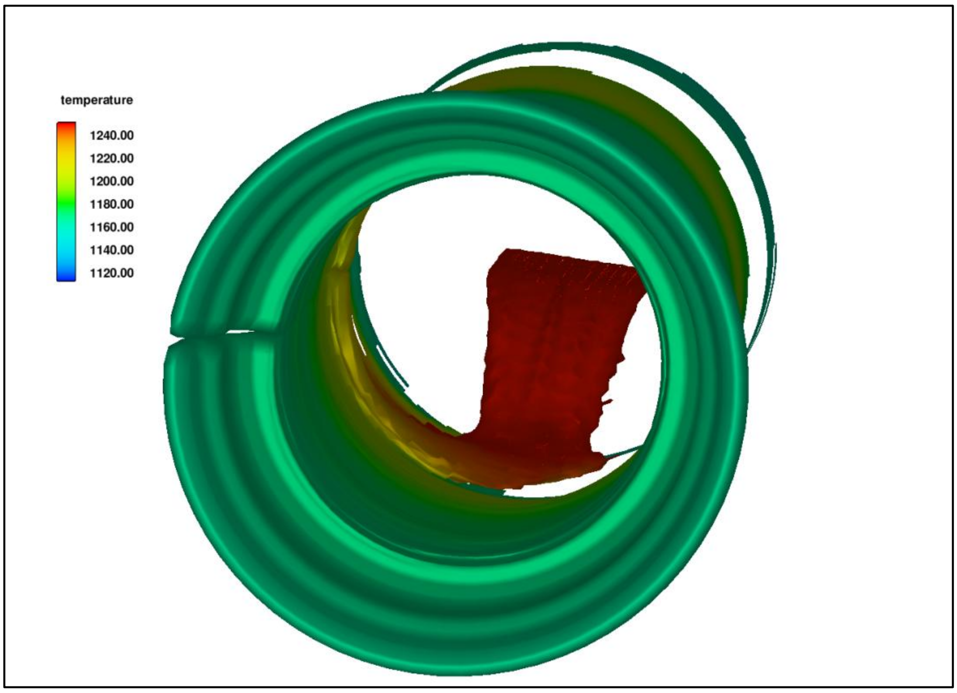

Figure 5. Simulated temperature distribution during filling of a pipe in a front view. The hot inflowing melt (in red color) is distributed along the inner tube-shaped steel mold due its rotation.

5. Conclusions

Following conclusions can be drawn:

- The De-Lavaud process can be simulated with Flow3D, taking advantage of the manifold modeling capabilities of this software
- Long calculation times (15 to 20 days) per pipe are common
- In comparison to reality, the influence of the main process parameters can be reproduced in the simulation
- Computed wall thickness matches within the relatively coarse grid size with measurements of standard pipes
- In simulation, each single process parameter can be varied and its influence on wall thickness can be studied
- Combinations of process parameters and hard (or not) to change parameter sets were simulated
- The impact of important parameters was identified.

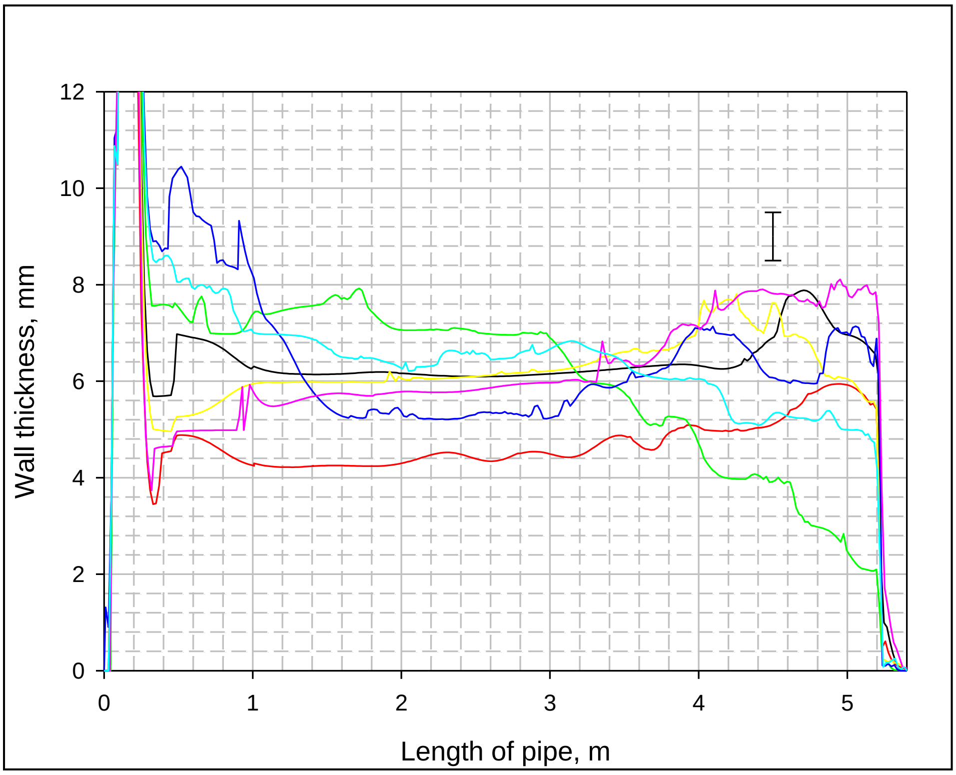

Figure 6. Examples for several simulated wall-thicknesses along the length of pipes using different process parameter sets.

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