One-Way Coupling of an Advanced CFD Multi-Physics Model to FEA for Predicting Stress-Strain in the Solidifying Shell during Continuous Casting of Steel

Johan Svensson¹, Pavel E. Ramírez López¹, Pooria N. Jalali¹ and Michel Cervantes²

¹ Casting and Flow Simulation Group, Swerea MEFOS AB
Aronstorpsvägen 1, SE 974 37 Luleå, SWEDEN
² Department of Engineering Sciences and Mathematics, Luleå University of Technology, SE 971 87 Luleå, SWEDEN

E-mail: pavel.ramirez.lopez@swerea.se

Abstract. One of the main targets for Continuous Casting (CC) modelling is the actual prediction of defects during transient events. However, the majority of CC models are based on a statistical approach towards flow and powder performance, which is unable to capture the subtleties of small variations in casting conditions during real industrial operation or the combined effects of such changes leading eventually to defects. An advanced Computational Fluid Dynamics (CFD) model; which accounts for transient changes on lubrication during casting due to turbulent flow dynamics and mould oscillation has been presented on MCWASP XIV (Austria) to address these issues. The model has been successfully applied to the industrial environment to tackle typical problems such as lack of lubrication or unstable flows. However, a direct application to cracking had proven elusive. The present paper describes how results from this advanced CFD-CC model have been successfully coupled to structural Finite Element Analysis (FEA) for prediction of stress-strains as a function of irregular lubrication conditions in the mould. The main challenge for coupling was the extraction of the solidified shell from CFD calculations (carried out with a hybrid structured mesh) and creating a geometry by using iso-surfaces, re-meshing and mapping loads (e.g. temperature, pressure and external body forces), which served as input to mechanical stress-strain calculations. Preliminary results for CC of slabs show that the temperature distribution within the shell causes shrinkage and thermal deformation; which are in turn, the main source of stress. Results also show reasonable stress levels of 10-20 MPa in regions, where the shell is thin and exposed to large temperature gradients. Finally, predictions are in good agreement with prior works where stresses indicate compression at the slab surface, while tension is observed at the interior; generating a characteristic stress-strain state during solidification in CC.

1. Background
Continuous Casting (CC) is the process of solidifying liquid steel into a usable shape (i.e. billets, blooms or slabs) by heat extraction from the melt through two cooling zones: the primary cooling zone consisting of a water cooled copper mould where initial solidification occurs and the secondary cooling zone consisting of a series of water sprays. The process is schematically shown in Figure 1. In the primary zone, the main heat transfer mechanisms are heat conduction through the shell, slag and
mould layers as well as convection to the cooling water in the mould; however, radiation also plays often an important role. A complex metal flow is found inside the mould with regions of high turbulence and large temperature gradients due to the feeding of hot steel through a Submerged Entry Nozzle (SEN). Additionally, the entire mould oscillates in order to prevent the liquid metal to freeze against the mould walls; while casting powder is continuously added from the top to insulate and lubricate the process. This powder melts when it comes in contact with the hot metal to form a protective slag cover (i.e. slag bed). The liquid slag also forms a thin layer which acts as a lubricant to reduce friction between the mould and solidified shell. This liquid layer solidifies against the cold mould to form an insulating layer (typically 1-2 millimetres), which controls the heat transfer in the mould. Finally, the secondary cooling zone takes place outside the mould, where the strand is further cooled through a series of water sprinklers at high pressure. The remaining liquid steel at the strand core solidifies within the secondary cooling zone before final cutting.

![Schematic view of the continuous casting process and a magnified view of the mould interior together with the different phases in the process (e.g. slag, steel, argon and air) based after [1].](image)

A variety of physical phenomena take place during CC such as heat transfer [2], multiphase flow [3], [4], solidification [5] along with mechanical stresses and strains [6-8]. Stresses are induced in the shell as it solidifies and cools causing shrinkage. Part of this shrinkage is due to phase transformations such as $\delta \rightarrow \gamma$ phase [9]. Shrinkage also causes stresses, plastic deformation and surface defects on the finished product, which in the long term can cause processing problems. Moreover, surface defects caused due to high stress concentrations are able to nucleate cracks and in the worst case scenario, breakouts. Breakouts may occur for a variety of reasons, but are often associated to a thin shell not able to withstand the ferrostatic pressure of liquid steel within the strand. This frequently combines with a lack of lubrication inducing high friction between mould and strand; and thereby, hot tearing. Breakouts are still a recurrent problem for steel producers, since the number of defects is higher with increased production [10] due to faster casting speeds (i.e. thin slab casting), higher throughput (i.e. larger slab formats) or casting of “difficult grades” (i.e. peritectics, duplex, trip steels, etc.).
Swerea MEFOS has developed a CFD-CC model able to predict a variety of phenomena including steel/slag interactions, heat transfer and solidification within the oscillating mould in order to simulate problem scenarios and optimize the CC process. Coupling the results from this CFD model to FE analysis allows more accurate predictions of stresses and strains during solidification and opens the door for more realistic breakout predictions.

2. MEFOS CFD - CC numerical model
Swerea MEFOS CFD-CC model predicts the multiphase steel-slag flow in the mould by solving the Navier-Stokes equations combined with the Volume of Fluid approach (VOF) based on the commercial code ANSYS Fluent v.141. The VOF model tracks the volume fraction of steel and slag by solving a unique set of momentum equations for both phases [11]. The volume fraction of the steel phase, $\phi_{\text{steel}}$, is derived by the continuity equation:

$$\frac{\partial}{\partial t} (\phi_{\text{steel}} \rho_{\text{steel}}) + \nabla (\phi_{\text{steel}} \rho_{\text{steel}} \vec{v}) = \sum_{p=1}^{n} (m_{p,\text{steel}} - m_{\text{steel},p})$$ (1)

Where $m$ is the mass transfer between phases; while the mixture density and viscosity are:

$$\rho_{\text{mix}} = \phi_{\text{steel}} \rho_{\text{steel}} + (1 - \phi_{\text{steel}}) \rho_{\text{slag}}$$ (2)
$$\mu_{\text{mix}} = \phi_{\text{steel}} \mu_{\text{steel}} + (1 - \phi_{\text{steel}}) \mu_{\text{slag}}$$ (3)

Here, $\phi$ may take any value between 0 and 1 to represent the steel phase fraction in a cell shared by the two fluids (i.e. steel and slag). A very fine boundary layer mesh (down to 25 µm) is used in order to resolve the slag-metal interface and ultimately, slag film infiltration and shell initiation. The k-ε RNG model with standard wall functions is used to include turbulent effects. The model solves heat transfer through the copper mould, SEN and one meter of strand below the mould exit. The heat transfer is given by the energy equation:

$$\frac{\partial}{\partial t} (\rho_{\text{mix}} H) + \nabla (\vec{v} (\rho_{\text{mix}} H + P)) = \nabla (K_{\text{eff}} \nabla T + (\tau_{\text{eff}} \vec{v}))$$ (4)

where $H$ is the enthalpy, $K_{\text{eff}}$ the effective thermal conductivity and $\tau_{\text{eff}}$ the effective viscosity. Data for specific heat and thermal conductivity is provided for all materials and phases as a function of temperature. Solidification is solved as a function of the heat transfer in the model. The solidification model is based on enthalpy where the liquid fraction in the mushy zone is defined by the lever rule:

$$f_l = \frac{T - T_{\text{solidus}}}{T_{\text{liquidus}} - T_{\text{solidus}}}$$ (5)

The pulling velocity of the solidified shell is defined by the temperature at which the steel is assumed to have enough strength to be pulled out in the casting direction or Zero Strength Temperature (ZST) [12]. The model represents one quarter of the mould (due to symmetry along the width and thickness of the slab) and contains 3 million cells including mould, strand (solid and liquid) and slag film/bed (powder, liquid, and solid). Heat is extracted through the water cooled copper mould by a convective heat transfer coefficient determined from the cooling-water flow-rate in the real plants. Figure 1 and 2 illustrate typical calculations with the model. Figure 2 shows a discharging jet of superheated metal leaving the SEN at high speed to dissipate its turbulent energy in the liquid pool; while Figure 3 shows the shell formation in 3D.

\[1\] ANSYS Fluent v.14 is a registered trademark of ANSYS INC. 2600 ANSYS Drive Canonsburg, PA 15317. USA.
3. CFD + FEM coupling

Fluid Structure Interaction (FSI) is an approach to predict the influence of flow on deformation in a body and vice-versa (e.g. where changes in the body geometry affect the flow surrounding it). Several standard solutions are readily available for FSI calculations in commercial software. However, these require a well-defined solid domain that does not change during the calculation process. Unfortunately, there is no such predefined domain during solidification since changes on the fluid flow affect the actual solid formation. This is a major hindrance for applying FSI to modelling of Continuous Casting. Another issue is that the solid-liquid interface often rests within one cell, whilst exporting of grids is often based on full cells to avoid connectivity problems. This results in a poor element representation of the smooth shell from CFD calculations into the FE environment. This occurs since mesh formulations required for CFD and FEM are often dissimilar (e.g. CFD often uses structured grids, while FEM typically uses tetrahedral mesh types). This issue is schematically shown in Figure 4.

FSI is also often referred as two-way coupling, where flow results are sent to the FEM model (e.g. one-way coupling) and back from the FEM model to the flow solver (e.g. two-way coupling). The present work is focused on one-way coupling as a first step towards a feasible FSI approach in the future. In order to translate the smooth shell from MEFOS CC-CFD calculations into FEM, a shell shape has been extracted for a time step where the solution had reached steady state (i.e. equivalent to stable casting conditions). The shell is processed in several steps: 1) CFD results are used to create surface geometries by exporting iso-surfaces in .STL-format, 2) the STL surfaces are combined to form a solid CAD body such that 3) the shell could be meshed with unstructured tetrahedral finite elements, to subsequently 4) map temperatures and loads from the original solution into the new mesh. The procedure is summarized in Figure 5.
Figure 4. Shell exporting procedure: a) Solidification results in FLUENT, b) Isolated shell (i.e. solid phase), c) Shell tip based on exporting full-cells resulting in poor representation, d) Schematic representation of full-cell exporting issues and e) Original shell profile on CFD results.

Figure 5. Schematic view of exporting procedure (left) and flow-chart summary (right).

The interior side of the shell is defined by the ZST iso-surface, while the exterior surface is defined by the steel VOF fraction equal to 0.5. The later iso-surface is not fixed in temperature and becomes colder close to the corners as the shell is cooled down from two mould sides. Both iso-surfaces are shown on Figure 6 with a colour map of temperatures. Further processing is required to read the shell exterior and interior surfaces into a FEA software as well as creating a solid body out of them to represent the final solidified shell. The procedure requires reading the STL-files which represent the surfaces with faceted triangular elements that can be read directly into the CAD software Siemens NX8.5. These geometries can; due to some tolerance issues, contain internal defects as seen in Figure 7a. The holes in the geometry can be eliminated and the faces smoothed with help of the decimate command in NX. Although this command modifies slightly the shell thickness; the final geometry becomes a very good approximation of the iso-values defining the original shape.

\(^2\) NX is a registered trademark of Siemens Product Lifecycle Management Software Inc. Wittelsbacherplatz 2, 80333 Munich, GERMANY.
Figure 6. Solid shell in 3D with the temperature map: Slab exterior (left) and interior (right).

The surfaces are stitched together by adding surfaces in the symmetry planes. Finally, a solid body is created as shown in Figure 7b. This solid body is finally exported with the STEP-format for meshing with unstructured tetrahedral elements in NX. Once the mechanical model is complete, the temperatures provided by the CFD simulation are mapped to the shell. An interpolation file is written containing the nodal temperatures for the entire fluid domain at a given time step. The shell model is then loaded into Fluent together with the interpolating file, so temperatures are mapped to the nodes in the new shell model. Thus, CFD results are used twice; firstly, to produce the shell model and secondly, to map the temperatures in the model. The solid body was meshed with around 36,000 tetrahedral elements. Each node was given the pouring temperature as an initial load for the thermo-mechanical calculation. The final temperature provided by the CFD simulation was set as one single linear-load step for the coupled thermal-stress analysis.

Figure 7. Shell at different stages of exporting procedure: a) STL faces stitched together showing exporting defects, b) Smoothed solid body and c) Final mesh with tetrahedral elements.
4. FE model theory and boundary conditions

The temperature distribution within the solid shell causes shrinkage and displacements, which ultimately lead to stresses and deformations. The total strain due to solidification and the temperature distribution is the sum of the elastic, inelastic (plastic) and thermal strain:

\[ \varepsilon = \varepsilon_e + \varepsilon_p + \varepsilon_T \]  

(6)

Thermal stresses are introduced on the solidified metal when the liquid feeding is unable to compensate for the shrinkage and thermal contractions [4]. The shrinkage over the phase transition can be estimated by the difference in density over the solid phase:

\[ \beta = \frac{\rho_s - \rho_l}{\rho_s} \]  

(7)

where \( \rho_{S,L} \) is the density of the solid and liquid phase respectively. Shrinkage is caused by phase transformations since the liquid phase occupies more volume than the solid phase. For a material with a temperature gradient over a length (\( \Delta T \)), the total strain (\( \varepsilon \)) can be computed by:

\[ \varepsilon = \Delta T \alpha L \]  

(8)

where \( \alpha \) is the thermal expansion coefficient and (\( L \)) is the original length. The strains for each node in three dimensions are determined by:

\[ \varepsilon_{ij} = \frac{1}{2G} \left( \sigma_{ij} - \frac{v}{1+v} \sigma_{kk} \delta_{ij} \right) \alpha T \delta_{ij} \]  

(9)

and the stresses due to the thermal strain are:

\[ \sigma_{ij} = 2G \left[ \varepsilon_{ij} + \frac{v}{1-2v} \delta_{ij} \left( \varepsilon_{kk} - \frac{1+v}{v} \alpha T \right) \right] \]  

(10)

where \( G \) is the shear modulus, \( v \) is the Poisson's ratio and \( \delta \) is the delta-Kronecker. Typical low carbon steel was used in the calculations with material data partly from literature and partly from Gleeble measurements. Tensile tests at different strain rates and temperatures were performed at Swerea KIMAB for low carbon steel and Kozlowski’s equation [2] was used to complete the material data for FE analysis.

\[ \dot{\varepsilon}_p = C \exp \left( \frac{-Q}{T} \right) \left( \sigma - a \dot{\varepsilon}_p e \right)^n \]  

(11)

The \( n \) and \( n_e \) coefficients were obtained by fitting the equation to the experimental stress-strain data available. Stress-strain curves for different temperatures and strain rates are presented in Figure 8 for a temperature range from 1100 to 1700 K under strain rates relevant to continuous casting (0.01s – 1s). As expected, the stress holds by the material decreases with increased temperature as well as decreased strain rate. The shell is constrained in three directions by defining symmetry conditions at the middle wide and narrow sides of the mould, along with fixed translation in the casting direction at the bottom. The shell is free to bend, while the mould wall and ferro-static pressure were excluded. Boundary conditions for the stress analysis are presented on Figure 9. The commercial software CAE/ABAQUS3 was used for the FEA analysis and the problem was solved with a general static approach with a single linear load step.

\(^3\) CAE/ABAQUS is a registered trademark of Dassault Systèmes Inc. Klara Södra kyrkogata 1, SE 11 152 Stockholm, SWEDEN
5. Results

CFD+FEM coupling makes possible to account for the effects of slag infiltration, mould oscillation and heat transfer variability on shell formation; as well as predicting subsequent strains-stress accumulation for specific casting conditions (e.g. steel grade, casting speed, slag properties, pouring temperature, etc.) including caster details such as SEN and mould design (e.g. taper, cooling channels, etc.). Results from the three-dimensional \( \frac{1}{4} \) shell section are shown in Figure 10.

A contact condition; defined by the mould wall, would indeed prevent the shell to bend as the results suggest. However, the shell is not in direct contact with the mould in the real caster since the liquid/solid slag layer sits between them. The maximum stresses are limited to a few nodes where the shell is thin. High values are generally found at the bottom, where fixed translation was defined. This should be ignored as it is a response to the boundary condition. The maximum von Mises stress is 40.31 MPa and is found at the narrow face close to the tip, where the shell is thin.

The majority of the shell though, is below a stress magnitude of 20 MPa which is line with expected magnitudes of in-situ experiments by Manchester University in an ongoing RFCS project.
[13]. The maximum displacement due to bending is found at the lower corner/symmetry plane of the wide face, where a maximum deflection of 40.4 mm is found. Results show that the shell is not shrinking towards the centre, but bending over the shell/mould interface. When comparing the deformed and the original shape of the bottom face of the shell, it is seen that the corner is more rounded after deformation. The result of thermal strains, Figure 10, shows both compression and tension within the shell. Preliminary results indicate compressive stresses at the exterior and tensile at the interior.

6. Discussion and limitations
As computer performance increases, also does the demand on better computer simulations. This includes the influence of fluid flow in thermo-mechanical analyses as well as shrinkage effects on heat transfer and flow simulations [2]. Simulating the multi-physics phenomena, (i.e. fluid flow, solidification, heat transfer and structure mechanics) during casting has been attempted in previous works [8, 14-16]. However, it lacks a detailed treatment of the slag phase in the calculations which is critical for the CC process. A two-way coupled model would be needed to fully predict the thermo-mechanical behaviour of the solidifying shell.

The simulated effect of thermal shrinkage and stresses is highly dependent on temperature via simulated heat fluxes and material properties. For instance, the heat conductivity and thickness of the slag film affect the heat conducted between the shell and mould. Hence, the heat conduction that defines shell growth is highly dependent on the distance between the solid shell and mould, which is calculated in the FEA. In reality, the shell is shrinking at the same time, which would change the amount of slag into the lubrication film; and consequently the shell thickness; so it can be argued that the change in geometry is affecting the flow field as well. Thus, minor changes in slag film thickness would immediately cause changes in heat transfer between the melt and the copper mould and thereby, affect shell growth. A more physically correct model would be able to couple the mechanical solution back to the fluid simulation and solve the flow with the updated, deformed shell. Ultimately, this would affect the overall thickness of the shell and the temperature distribution in the mushy zone. A two-way coupling may be able to clarify some of these issues; but so far, the model presented is only considering the influence of flow pattern and thermal loads on the stress state. Further investigations can be done to find out how this mechanical behaviour really affects the solidification behaviour into the mould. However, there is no existing FSI approach able to cope with a non-prescribed solid body in the analysis. Moreover, even though the shell is defined as a solid within FLUENT, it is still a fluid with very high viscosity (which can be related to a solid body).

A simple solid shell may be created and used for the purpose of using a standard FSI approach. However, a prefixed shell beats the purpose of the CFD model since the intricate shape of the shell is derived from transient calculations including slag infiltration. An adapting mesh could also be used for the solidification front in FLUENT to increase the model accuracy. However, it increases the computational time considerably. In addition, symmetry conditions have been used in order to decrease the computational time. This may be a source of error as all gradients in the symmetry planes are set to zero. However it is a well-known fact that metal flow in CC is highly asymmetric and unsteady[17]. Thus, the shell is also expected to be irregular and non-symmetric. The material properties used in the mechanical analysis are partly interpolated from Gleeble measurements since it is extremity difficult to obtain material stress-strain data at semi-solid temperatures. This conveys a possible source of error on the input data. Finally, the approach of performing a static solution of the final thermal loads from a pre-defined temperature does not include any temperature history of the nodes during transient solidification. These issues are under current investigation by the authors.

7. Conclusions
A procedure for coupling CFD results to FEA by exporting iso-surfaces, creating a CAD geometry and mapping loads has been successfully developed in the present work. The following conclusions can be drawn from the presented work:
• Transferring of data including features such as temperature, pressure, shape and surface irregularities from CFD to FEM was proven possible.
• The coupling also makes possible to evaluate the stresses and strains within the solid shell based on CC-CFD results for a particular time snapshot during transient calculations.
• Thermo-mechanical results show that stresses are concentrated on areas close to the corner and where the shell is thin, with stress magnitudes in good agreement with existing data.
• Results show compressive stresses at the shell exterior and tensile at the shell interior.
• The magnitude of the strain results indicates plastic deformation of the shell, which provides a characteristic stress map for continuously cast products.

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