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Simplified models for high pressure die casting simulation

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Abstract

The simulation of the High Pressure Die Casting (HPDC) process is a complex type of simulation. The industrial procedure is based on consecutive manufacturing cycles that must be taken into account in the simulation. Moreover the part geometries use to be complex and the alloy is injected at really high velocities. All of that usually implies long calculation times that in complex cases can lead to several days.
Sometimes, the circumstances require to have available a fast solution despite involve a loss of accuracy. The work presented hereafter discusses different possibilities to simplify the HPDC simulation models together with their benefits and drawbacks.
The simplified simulation models have been validated against a detailed 3D simulation model, previously correlated with experimental results.
The comparative, shows that the use of simplified models may be a solution that makes possible a big reduction in calculation times maintaining a reasonable level of accuracy.

Keywords: finite elements; numerical simulation; heat transfer; HPDC; metal casting

1. Introduction

The numerical simulation of metal casting processes is a complex type of simulation. As Bonollo and Odorizzi explains at reference [1], it typically requires to solve the filling of the cavity governed by the fluid-dynamics laws,

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the solidification and cooling according to the heat transfer laws and some additional effects related with the physical metallurgy.

The fluid-dynamics simulation implies to solve the Navier-Stokes equations, see [2], which is always a very complex calculation. The Fourier equation that governs the heat transfer, see [3], must be also solved. The solution to both phenomena, fluid-dynamics and heat transfer, must be coupled, see [4]. In addition some physical effects related with the physical metallurgy are included, typically the determination of the shrinkage defects and in more advanced calculations, aspects as the microstructure types or the grain sizes as Dantzig and Rappaz explain at reference [5]. The numerical complexity is increased by the fact that the solution must be calculated for transient regime and usually complex geometries. This is especially true for the case of the High Pressure Die Casting (HPDC) simulation, where part geometries are usually considerably complex and the alloy is injected at really high velocities.

All of that usually imply long calculation times. In complex cases can lead to several days or indeed several weeks, in spite of the advances experimented during last years in hardware and software technologies.

Despite these difficulties, at present the numerical simulation is widely used by the metal casting industry. Sometimes the industry needs to predict the metal casting process as reliable as possible. So, it is needed to go to detailed models able to reproduce accurately the situation at the industrial plant and wait for long time until the solution is reached. But sometimes a fast solution is required although it implies a loss of accuracy. Typical situations are related with the industrial necessities, for example during the offer phase or for the quick evaluation of several alternatives. But there are other situations where this fast response is also interesting, as for example, during the adjustment process of the simulation models.

The adjustment or correlation of the simulation models is referred to the adaptation of the simulation model to be able to reproduce appropriately the data collected as reference during several controlled experimental tests. A useful methodology is the use of inverse techniques. Temperatures at several points are registered during the experimental manufacturing of a prototype and used later as reference to adjust the modelling. The simulation model is considered adjusted when temperatures predicted by simulation agree well with those registered experimentally. This type of methodology has been proved satisfactorily by different authors for different metal casting processes, as are the cases of references [6–9] for the investment casting process and the references [10–13] for different processes with metallic molds including HPDC.

One of the drawbacks of this methodology is its iterative nature. The model parameters are modified, the simulation is executed, results are compared with experimental measurements and the parameters are modified again until reach the adjustment. The number of simulations that is needed to perform until reaching the adjustment may be very high, from several tens to several hundreds. So if each model calculation requires several hours or even several days the mission is almost impossible. In these cases the use of a simplified model able to provide a fast response is very interesting to perform first approximations. The final adjustment must be performed with a detailed model able to reproduce the process with accurate enough, but the use of simplified models permits an important reduction of the time needed to reach the adjustment.

This methodology, the use of a simplified model for first approximations during the adjustment process of a HPDC, has been successfully used in other work of the authors verifying its applicability, see reference [13]. Although the results of that adjustment are shown in the cited reference, the use of the simplified model is only succinctly mentioned.

It is felt that some aspects, advantages and limitations, of the use of simplified models are of general interest for the research community. For this reason the work presented hereafter discusses different possibilities to simplify the HPDC simulation models, evaluating the associated lack of accuracy versus the velocity improvement.

2. Methodology

The HPDC is a continuous production process based on consecutive manufacturing cycles. At beginning of the manufacturing process the mold is usually too cold preventing the cavity filling. The alloy freezes partially during the injection and does not fill completely the cavity. The successive cycles go increasing the mold temperature but until it is not hot enough, the quality of the manufactured part will not be good, presenting surface defects and/or internal porosity.

The detailed simulation of the HPDC process requires include the simulation of the preheating cycles until reaching the mold thermal stabilization. Notice that thermal stabilization does not mean uniform temperature, as a thermal gradient exists along the mold geometry which also varies during the cycle stages.

Several simplifications related with the inclusion of the preheating cycles, the phenomena to include in calculation, as well as geometrical simplifications have been evaluated in terms of accuracy and calculation times. The methodology followed to evaluate the accuracy of the simplified models has been the comparison of their results against the results obtained from a detailed simulation model. This detailed model used as reference has been previously correlated with experimental results, see [13]. The software used to perform the simulation is a commercial finite element software called ProCAST. It is especially focused on metal casting processes simulation combining several solvers that make possible the resolution of the computational fluid dynamics (CFD) coupled with the heat transfer problem, including the prediction of shrinkage defects. It includes also additional modules able to perform for example thermo-mechanical analysis or microstructural predictions. The alloy temperature considered corresponds to a point located in the center of the transversal section of the cast part. The mold temperatures have been collected at several points located on the contact face between the fixed and movable plates of the mold, into and near the cavity.

2.1. Simplifications considered

- Simulation of the pre-heating cycles. A priori the inclusion of the pre-heating cycles in the simulation seems highly advisable. It not only avoids the necessity to estimate the average temperature for the stabilized mold at the cycle start but also it provides the temperature distribution along the mold. In other case, it is only possible to assign a unique value of initial temperature for the whole mold. The number of cycles to simulate must be the necessary to reach the mold thermal stabilization (typically between 5 and 20 cycles). Of course it implies a big increment in time calculation as it is equivalent to perform 5 or 20 simulations instead of one. For this reason the influence of the inclusion of the pre-heating cycles has been studied.
- Thermal and flow or only thermal analysis. To restrict the simulation only to the heat transfer analysis clearly reduces the information provided by results. In this case no information is obtained about the flow behavior during filling as velocities or flow paths. But in some cases the thermal results may be enough if they are representative of the real thermal behavior. As thermal only analysis is usually much faster than the combined thermal and fluid analysis, the differences between both cases have been analyzed.
- Geometrical simplifications. Finally the influence of the geometrical simplification has been considered. A pseudo-2D model corresponding to one slice of the mold has been simulated and compared with the detailed model results. In this case the reduction expected in calculation times is very significant but the question to solve is its influence in the results accuracy.

2.2. Description of the detailed model

The detailed model used is a 3D finite element model formed by 495.999 tetrahedral elements and 100.593 nodes. The model geometry includes the cavity and the fixed and movable plates of the mold. In this case the cavity geometry is quite simple (cylindrical shape Ø50 mm and 250 mm length). The reason is that it does not correspond to an industrial part but with a prototype specifically designed to be used for the correlation of the simulation modelling.

The injected alloy corresponds to AlSi9Cu3, widely used in aluminum die casting due to its good castability (improved by the silicon content) combined with a medium strength (enhanced by the copper) and a good machinability. The mold is manufactured in steel H13, a tool steel with excellent wear resistance and good thermal shock resistance very used in manufacturing of die casting molds. The chemical composition of AlSi9Cu3 and H13 are included in Table 1 and Table 2 respectively. The material properties of the mold and alloy, all of them temperature dependent, have been assigned to the corresponding volumes. The heat transfer coefficients assigned between them are temperature dependent but also time dependent to take into account the cycle stages (mold plates open, closed, etc.). Finally the boundary conditions have been assigned not only to define the cooling conditions but also to define the alloy injection conditions.

Table 1. Chemical composition % of AlSi9Cu3

Si	Cu	Mn	Mg	Fe	Ni	Pb	Sn	Ti	Zn	Al
8.0-11.0	2.0-3.5	0.1-0.5	0.1-0.5	Max 0.80	Max 0.3	Max 0.2	Max 0.1	Max 0.15	Max 1.2	Rest

Table 2.Chemical composition % of H13 steel

C	Cr	Mo	Si	V	Fe
0.32–0.40	5.13–5.25	1.33–1.4	1.0	1.0	≥90.95

3. Results and discussion

3.1. Simulation of the pre-heating cycles

The time needed to solve only one cycle with the detailed model, considering the problem thermal and flow, is equal to 6.9 hours. This calculation time has been obtained in a PC with 2 CPUs Intel ® Xeon ® E5335 quad core @ 2.00 GHz and 8 Gb RAM. Notice that although the PC has 2 quad core CPUs, the simulation software only use one of these eight cores.

The inclusion in the simulation of 5 or 20 preheating cycles is equivalent to perform 5 or 20 simulations of one cycle, with the consequent increment in the calculation time. So, seems very interesting to study the influence of including or not the pre-heating cycles as it could signify an important time reduction (5 to 20 times).

The evolution of the mold temperature during the pre-heating cycles simulation can be observed in Fig. 1. Fig. 2 shows the temperature results obtained including or not the pre-heating cycles in the simulation, where is observed that the loss of accuracy is low. Nevertheless, the mold initial temperature used for the no pre-heating case has been estimated based on previous results. In case of a worst estimation of the initial temperatures the differences are bigger. Fig. 3 shows the results obtained considering different values for the initial temperature of the mold (± 20ºC). As can be observed the differences in results are more pronounced, although the variation applied to the initial temperatures is only equal to 20ºC.

So, it seems that the advantage of including the pre-heating cycles in the simulation is more related with the correct estimation of the average mold temperature, than with the mold temperature distribution. In cases where it is possible to estimate correctly the average temperature of the mold plates interfaces, the pre-heating cycles simulation may be omitted. Nevertheless, considering the difficulty of estimating this average temperature, it is advisable to perform the simulation of the pre-heating cycles.

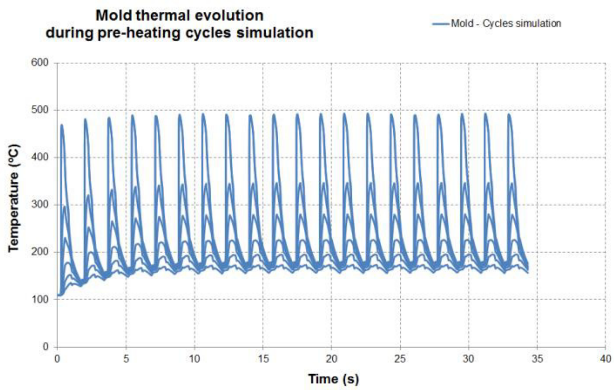

Fig. 1. Mold thermal evolution during pre-heating cycles simulation

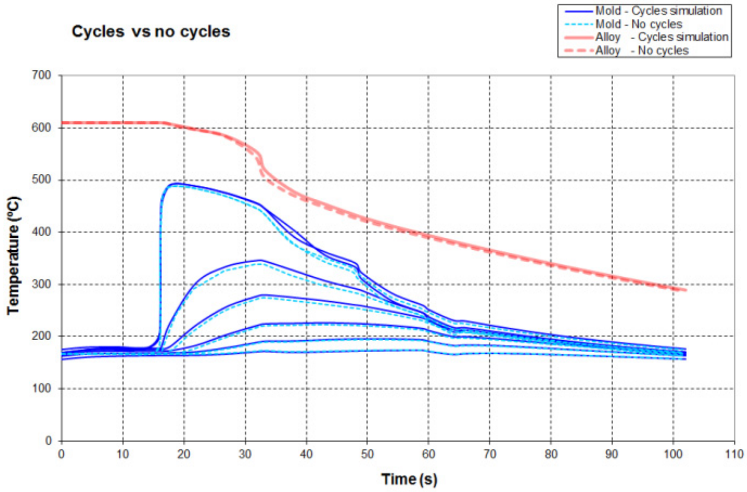

Fig. 2. Temperature results including or not the pre-heating cycles in simulation

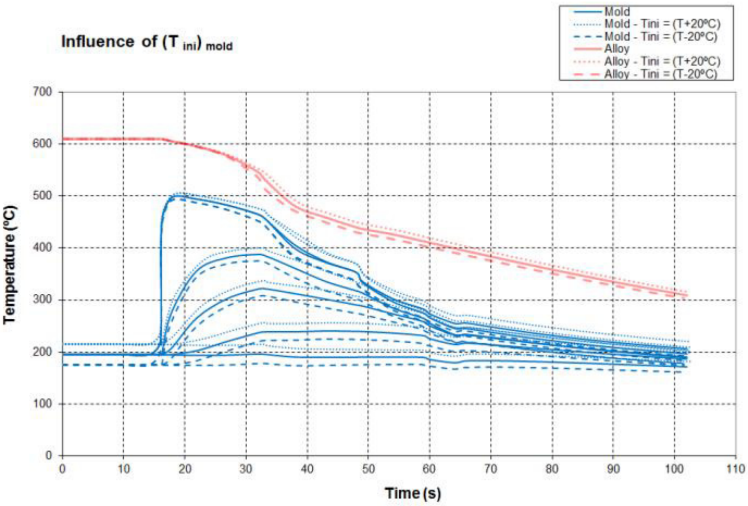

Fig. 3. Temperature results for different initial mold temperatures

3.2. Thermal and flow or only thermal analysis

The calculation time needed to solve the thermal and flow problem, that is, the fluid-dynamics and heat transfer coupled analysis, is much higher than in the case restricted to only heat transfer calculation. The fluid-dynamics and heat transfer coupled analysis needs 6.9 hours for the simulation of 1 single cycle with the detailed model, in the previously mentioned PC, while the time needed for the case restricted to only heat transfer calculation is equal to 0.3 hours.

The drastic difference existing in calculation times makes patent the interest of limiting the simulation to the heat transfer analysis when possible. Fig. 4 contains the temperature results for the case where only heat transfer analysis has been performed and the case including the thermal and flow analysis. As can be observed, the temperature results are similar and the lack of accuracy that implies the restriction to only thermal analysis is clearly compensated with the important reduction in calculation times.

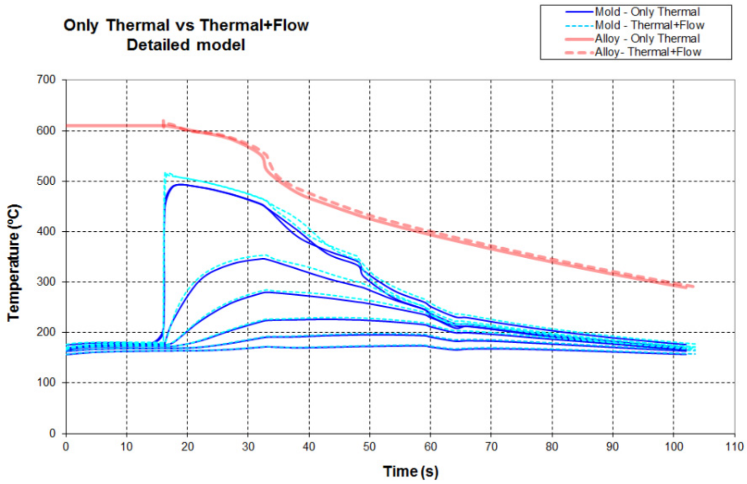

Fig. 4. Detailed model. Temperature results for only thermal vs thermal and flow.

To restrict the simulation to only heat transfer analysis is a good option in these cases where the interest is focused on the thermal distribution and not in the flow behavior during filling (velocities, flow paths, etc.). One of these cases is the simulation of the pre-heating cycles, as the objective of this analysis is to obtain the stabilized temperature of the mold.

So, the methodology sometimes applied of limiting the pre-heating cycles simulation to the heat transfer analysis, seems the best option to maintain the calculation times in reasonable values with a low loss of accuracy. Once the mold thermal distribution is achieved, is possible to perform the thermal and flow simulation of the injection process assigning the obtained thermal distribution as the mold initial temperature.

3.3. Geometrical simplifications

The geometrical simplification applied, is based on the concept that the heat transfer across the mold is mainly two-dimensional. So, only a slice of the mold (see Fig. 5) has been selected to be used in the simplified simulation.

This section, the mold and the cavity have been discretized by means of a finite element mesh. This mesh (see Fig. 5 right) is formed by 19172 nodes and 79965 tetrahedral elements forming a pseudo-2D model. The material properties, heat transfer coefficients and boundary conditions applied are the same used in the detailed 3D model.

For people familiar with simulation models is evident that this pseudo-2D model is not completely representative of the real case. In fact, it is not possible to perform the cavity filling simulation. But it can be useful in these cases where the interest relies in the heat transfer analysis.

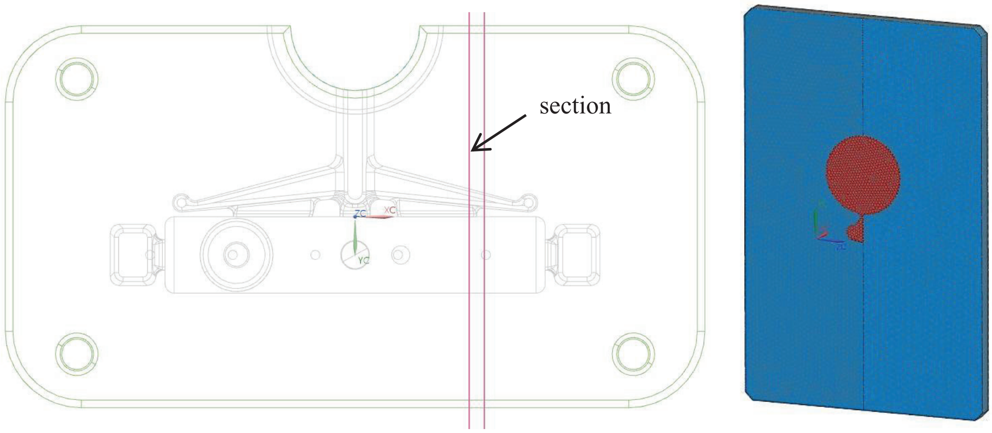

Fig. 5. Drawing of the HPDC mold and the section selected for the pseudo-2D model (left). Mesh corresponding to the pseudo-2D model (right)

The differences in calculation times for the detailed model and the pseudo-2D model are very significant (see Table 3). In this case the lack of accuracy is more pronounced than in previous cases, as can be observed at Fig. 6. But considering the drastic differences in calculation times, this option may be very advisable to some cases where the accuracy requirements are not very high or when time restrictions are very important.

Table 3. Calculation times

Analysis type	CPU time (minutes)
Detailed model	
1 cycle (heat transfer only)	21
20 cycles (heat transfer only)	425 (7.1 hours)
Pseudo-2D model	
1 cycle (heat transfer only)	2
20 cycles (heat transfer only)	43

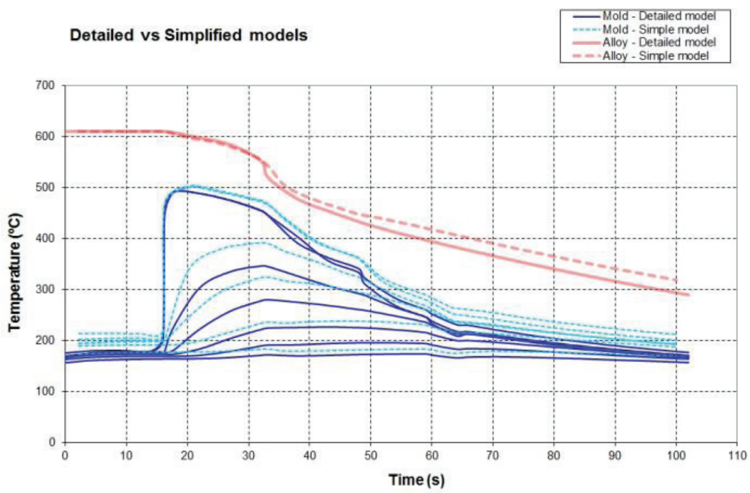

Fig. 6. Detailed vs pseudo-2D model temperature results (after 20 cycles)

4. Conclusions

The simplified simulation models have been able to reproduce appropriately the thermal behavior of the mold and of the cast part, with significant reduction in calculation times. The model validations have been achieved by comparison with the results of the detailed model previously correlated, with experimental data.

The inclusion of the pre-heating cycles in the simulation is highly advisable. The main reason is the difficulty to estimate the mold average temperature in other case. Relating to restrict the simulation to the heat transfer analysis, is a good alternative when the interest is only focused in thermal behavior. On his behalf, the use of pseudo-2D models is advisable only in these cases where the accuracy must be sacrificed to reduce calculation times.

In base on the obtained results, the next procedure seems the most advisable option. Execute first a simulation of the pre-heating cycles but limiting the analysis to the heat transfer. Next execute a second simulation including the thermal and flow analysis. The mold temperatures obtained as result of the first simulation must be assigned as the initial temperatures of the mold for this second simulation. In both cases the 3D detailed model must be used.

In the cases where time restrictions are important, the use of pseudo-2D models is a good alternative. If the loss of accuracy in the results that it implies is acceptable, its use makes possible a drastic time reduction (10 times compared with detailed one). This alternative has been validated by its use during the preliminary phases of the adjustment process of a HPDC model, see [13].

Acknowledgments

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