THE SIMULATION OF THE STEADY-STATE CONDITIONS OF ALUMINIUM DIRECT-CHILL CASTING

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Abstract. In this research, the simulation of aluminium direct-chill casting has been achieved focused on the fluid flow and thermal conditions. Control Volume Method is used applying the NovaFlow&Solid simulation software and the JMatPro software was used for the calculation of the material properties. 6 ingot geometries were examined using 4 commercial alloys. A hybrid method is developed for the calculation of the material properties and as a result, the temperature profiles and the liquid phase is analysed.

1. Introduction
The second most economically important metal is aluminium, around 80 million tonnes of aluminium cast every year and more than half is direct-chill cast [1]. Direct-chill castings can be cast from primary metal or secondary scrap materials to create intermediate products for remelting or for forming, such as rolling. The quality of direct-chill castings has an effect on the yield and the properties of the final products used. Typical products are used in transportation, automotive sector, building and electronic industry. The direct-chill casting companies, therefore seek to control the quality of the castings, while minimising costs, maximising capacity, at the same time producing with minimal environmental impact.

2. Modelling and simulation of the direct-chill casting process
Direct-chill casting appears to be a simple process involving the cooling and solidification of liquid metal into an ingot; however, the physical phenomena taking place are complex, with many interactions between heat transfer, fluid flow, and stresses. The development of mathematical and physical models has paralleled the development of technology and continually expanded our understanding of these complex phenomena [2]. From the very beginning of direct-chill casting development, it became clear that the proper choice of process parameters makes all the difference in successful casting. See the examined device in Figure 1. [3].

Figure 1. Direct-chill casting device
Many modelling and simulation methods can be employed for direct-chill casting, such as physical modelling, empirical relationships, statistical methods, analytical solution methods, inverse methods and numerical methods. The most common numerical methods implemented in technological simulation software are Finite Difference Method (FDM), Finite Volume Method (FVM) and Finite Element Method (FEM) [4].

Finite Difference Method is a numerical method where a complex problem is solved by discretizing the complex region of problem (domain) into a finite number of small portions (control volumes). Material properties are assumed to be constant throughout the volume. Therefore, for high accuracy of the results, the domain should be divided into a maximum number of control volumes possible taking into account the computational time. FDM is a differential scheme which is the approximation of Taylor series expansion. Calculations are iterative and done at a predetermined time-step. The results can be stored at the end of each time-step or after a pre-determined number of steps [5].

Unlike FDM, Finite Volume Method is an integral scheme. Although the idea of discretizing the domain into small volumes remains the same, the use of integral formulations is advantageous in treating the Neumann boundary continuous as well as that of discontinuous source terms due to their reduced requirements on the regularity or smoothness of the solution. It is possible to solve to be a control on mesh elements at the borders of the geometry. With cubic elements in the volume and border cells at the boundary, the simulations are much faster and accurate. Also, the method provides filling of a necessary fraction of a cell instead of filling cell by cell [6].

The Finite Element Method discretizes the complete domain of the problem into small pieces (a.k.a. elements). Each element is made up of nodes (corner points) and edges, which store material properties to be used in the computation. The solution is done by using these values to determine a quantity for these specific points (a.k.a. Gauss points) within the elements. The position of these points in elements is a function of the integration applied, initial coordinates of the nodes, and the element shape. Values of variables, which are considered to be constant in FDM/FVM across the elements, are calculated using some interpolation function. The treatment of time in an iterative and step-wise manner is similar to FDM/FVM [7].

2.1 The simulation model
At this point, it should be emphasized that a mathematical model of a technological problem always is an approximation of the original problem no matter the solution method. Thus, an analytical method, although giving the exact solution to the mathematical problem, results in an approximate solution to the problem. It therefore only makes sense to take all the approximations into account if the value or applicability of a solution to a technological problem should be evaluated. Exact consistency between the mathematical solution and the mathematical model is thus not enough to ensure a good solution to the original problem, even though a certain degree of accuracy in the mathematical solution is always desirable [8].

The physical phenomena behind a technological problem should be identified and a mathematical model must be written. This mathematical model must be solved using an analytical or a numerical solution and the physical interpretation of this mathematical solution should be done for the technological solution. Especially in manufacturing processes such as casting, the misinterpretation of otherwise correct mathematical results could lead to wrong conclusions, and hence to no solution of the originating problem [9].

In this paper, the Finite Volume Method is used to solve the material- and heat transport processes using the commercial software NovaFlow&Solid. The concept of simulation experiments can be seen in Figure 2.
Pre-processing, id est definition of the problem. The first step is to define the geometry of the casting system into a discrete number of segmented volume elements for the subsequent calculations. Before the equations that govern the filling and solidification processes can be solved, the necessary thermophysical material data must be available. Apart from the material data themselves, other relevant process parameters have to be defined. Initial conditions for the unknown quantities and boundary conditions for the unknowns must be defined. Other relevant information also needs to be input, so that all the factors that affect the filling and solidification of the casting can be accounted for.

Main-processing, id est the calculations. After the geometry has been defined and the mesh generation has been performed, the most demanding part of the numerical simulation follows in respect of both the algorithmic development and the requirements for computer capacity, solution of the governing equations. The most usual approach here is to solve all the basic equations, this being a prerequisite for simulating all relevant casting problems of a technical nature. It is clear that these calculations, in which primitive fields such as temperatures, displacements, stresses, velocities, pressure, etc. are determined, require the solution of the governing differential equations.

Post-processing, id est presenting the results. After the computations, the resulting basic fields (temperatures, velocities, pressure, displacements, stresses, etc.) should be presented appropriately. The results are often made more instructive by colour displays and curves.

In the given experiments the material properties, the 3D geometry and the initial conditions were modified for the proper calculation results.

2.2 Material properties

Before the equations that govern the filling and solidification processes can be solved, the necessary thermophysical material data must be available. For the calculation of the temperature field in the casting system, information is required about the densities, specific heat capacities, and thermal conductivities for all of the materials in the casting system (cast metal, mould, cores). Besides, the latent heat of fusion of the cast alloy is required. To calculate velocities and pressures during mould filling, the viscosity of the liquid metal alloy is also needed. Since all of these quantities can vary significantly with temperature, the property variations with temperature must be considered as part of the simulation.

The source of the thermophysical material data can be calculation, literature, data bank and measurement. The examined alloy compositions (wt%) can be seen in Table 1.

| Alloy | Si (wt%) | Fe (wt%) | Cu (wt%) | Mn (wt%) | Mg (wt%) | Cr (wt%) | Zn (wt%) | Ti (wt%) | Al (wt%) |
|------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 3117 | 0.3     | 0.2     | 0.8     | 1.2     | <0.1    | <0.1    | <0.1    | 0.1     | rest    |
| 4147 | 11.8    | 0.2     | <0.1    | <0.1    | 0.2     | <0.1    | <0.1    | <0.1    | rest    |
| 5083 | 0.1     | 0.2     | <0.1    | 0.5     | 4.4     | <0.1    | <0.1    | <0.1    | rest    |
| 8006 | 0.1     | 1.3     | <0.1    | 0.4     | <0.1    | <0.1    | <0.1    | <0.1    | rest    |
The chemical compositions are measured average values, calculated from industrial batches. Based on the chemical composition and the cooling velocity of the ingot, which is calculated by a preliminary simulation (0.0544°C/s), the thermophysical material data are calculated with the JMatPro software. The JMatPro software calculates a wide range of material properties for multi-component alloys. By several iterations, the following material data are calculated as a function of temperature in every 2°C cooling step: heat conduction, specific heat, density, viscosity, heat transfer coefficient and latent heat. This means approx. 1700 material data per alloy. These material properties must be installed to the NovaFlow&Solid simulation software for further calculations.

In the NovaFlow&Solid simulation software, a specific databank is used for the material and heat transfer calculations. A standard aluminium foundry alloy composition (EN AC-46000) is used as a so-called donor alloy, and the values of this, e.g. phase diagram and material properties, are used for the creation of the new alloy properties by the following routine:

1. Study temperature-thermophysical data values of the donor alloy.
2. Determination of the thermophysical data on the NovaFlow&Solid curves.
3. Find these values on the JMatPro curve.
4. If the examined value can be found on the JMatPro curve and the temperature value of it fits the NovaFlow&Solid values, use the data of JMatPro. (See Figure 3.)
5. If the examined value cannot be found on the JMatPro curve or the temperature value of it doesn’t fit the NovaFlow&Solid values, use the data of Novaflow&Solid databank. (See Figure 3.)
6. Create the new alloy in the NovaFlow&Solid databank.

![Graph showing temperature vs. density and thermal conductivity]  

**Figure 3.** Corresponding values of thermal conductivity and non-corresponding values of density

3. **Design of Experiments**

First, the filling of the crystallizer is analysed, where the geometry consists of the die, the primary cooling and the starting block in the initial position. Later on, the solidification of the ingot is examined based on several process parameters. In this case, the geometry is completed with the secondary cooling. The mid-line 3D section of the examined CAD models can be seen in Figure 4.
Figure 4. Left side: crystallizer geometry; Right side: ingot geometry

The design of experiments, the main process parameters and the number of iterations (NoI) can be seen in Table 2.

| Nr. | Action                                           | NoI | Alloy  | Ingot mm | Temperature °C | Pouring kg/s |
|-----|--------------------------------------------------|-----|--------|----------|---------------|--------------|
| 1   | Filling and solidification of the crystallizer    | 4   | 4147   | 520x1590 | 705           | 2.27         |
| 2   | Definition of the shrinkage cavity               | 2   | 4147   | 520x1590 | 705           | 65           |
| 3   | Solidification of the divided ingot              | 1   | 4147   | 520x1590 | 705           | 65           |
| 4   | Solidification of the 4147 alloy                 | 3   | 4147   | 400x1460 | 680           | 65           |
| 5   | Solidification of the 5083 alloy                 | 3   | 5083   | 465x1120 | 675           | 65           |
|     |                                                  |     |        | 465x1620 |               |              |
| 6   | Solidification of the 8006 alloy                 | 3   | 8006   | 520x1340 | 705           | 65           |
| 7   | Solidification of the 3117 alloy                 | 3   | 3117   | 330x1310 | 715           | 65           |

4. Simulation results

4.1 Flow analysis

In the filling analysis of the crystallizer, the 4147 alloy is poured to the cavity with the initial temperature of 705 °C. The alloy is poured to the cavity by a round shape stream, where the radius is 30.0-80.0 (mm), using a 91.5 (mm) defined pressure height and a defined flow. Three cases were examined: slow pouring, fast pouring, and ideal pouring.

In the case of slow pouring, the flow was 2.0 (kg/s), the heat loss of the liquid alloy is too fast, and the metal solidifies to the surface of the crystallizer layer by layer, which causes overlapping and cold flow defects. See Figure 5. left side, liquid phase scale: 5-95 (%).

In the case of fast pouring, the flow was 27 (kg/s), the metal flows with a lot of turbulences and splashes in the crystallizer. Turbulence causes air entrapments and surface oxide bifilms which is one of the main sources of shrinkages. See Figure 5. right side, velocity scale: </>0.5 (m/s) [10].

The so-called ideal pouring flow was calculated in the following way. For gravity castings the pouring time (s) can be calculated by the following empirical relationship: pouring time is equal to the square root of the double amount of metal (kg). The relationship is not scientific but works well in case of heavy castings. In the next step, the amount of the poured metal is divided by the pouring time, which gives the pouring flow: 13.7 (kg/s). In case of ideal flow the velocity of the metal is lower than...
0.5 (m/s), which means that the movement of the metal is turbulence-free and undisturbed, no pouring defects developed.

4.2 Shrinkage analysis

In the solidification calculations, the steady-state conditions were examined, because the moving of the ingot was not possible to observe. In real life, the length of the ingots is 5400 (mm). To determine that which section of the ingots should be examined a so-called shrinkage analysis is implemented where no feeding is applied in normal gravity conditions. The mid-line 3D section of the examined CAD model can be seen on the right side of Figure 4. The initial parameters can be seen in Table 2. Further initial parameters are material of the die and starting block: EN AW-3003. The temperature of the die and starting block: 20 (°C). The flow of primary cooling: 27.7 (l/s). The results of the shrinkage analysis in the mid-line 3D section can be seen in Figure 6.

A calculated depth of the shrinkage hole is 538 (mm). The weight of the poured metal is 1985.3 (kg) and the volume of the shrinkage is 6.3% of the initial geometry.

4.3 Solidification analysis

At the starting point of the shrinkage analysis, the whole ingot geometry had a uniform temperature. To approach the real-life conditions, the partitioning of the ingot is needed. The sections of the ingot are calculated by the parameters of the CAD model. The mid-line 2D section of the divided ingot with the initial temperature of the metal, and the thermal conditions, can be seen in Figure 7. The colours correspond to the earlier models. The ingot geometry is divided as follows: ingot height in the crystallizer is 140 (mm), ingot height in the starting block is (120) mm, the middle part of the ingot is divided into 4 times 200 (mm).
Thermal conditions

| Zone   | Sideward the heat is added to the crystallizer. In +Z direction the heat is added to the environment. In –Z direction the heat is added to the melt. |
|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Zone 2 | Sideward the heat is added to the secondary cooling. In Z direction the heat is added to the melt.                                                                                                  |
| Zone 3 | Sideward the heat is added to the secondary cooling. In +Z direction the heat is added to the melt. In –Z direction the heat is added to solidified parts.                                                |

Figure 7. Divided ingot geometry with initial temperatures, and the thermal conditions

The solidification of 4 alloys and 6 ingots are examined, here the results of the 520x1340 ingot are presented (alloy 8006). The initial parameters of the calculation can be seen in Table 2. and Figure 7. The solidification of the ingot in the mid-line 3D section can be seen in Figure 8. Liquid phase scale: 5-95%.

Figure 8. Solidification of the 520x1340 ingot geometry

For further analysis of the solidification process, thermocouples are defined in the mid-line section of the crystallizer with 23 (mm) distances. The cooling curves of the thermocouples can be seen on the left side of Figure 9. The results of the analysis of the phase fraction of the liquid phase can be seen on the right side of Figure 9.
5. **Summary**

In this research, the simulation of aluminium direct-chill casting has been achieved focused on the fluid flow and thermal conditions. The background of the direct-chill casting process is presented based on the literature and the simulation possibilities are considered. The material properties of the examined alloys are calculated based on industrial data using JMatPro software and the databank of the NovaFlow&Solid simulation software. All the simulation experiments are accomplished with the NovaFlow&Solid platform using Control Volume Method. By the help of fluid flow analysis, optimal casting parameters were developed and the solidification process in steady-state conditions are examined. All examined variables - such as ingot geometry, alloy and cooling conditions - were examined and the specified simulation process is suitable for the analysis of the filling and solidification processes.

**Acknowledgements**

The described article was carried out as part of the EFOP-3.6.1-16-2016-00011 “Younger and Renewing University – Innovative Knowledge City – institutional development of the University of Miskolc aiming at intelligent specialisation” project implemented in the framework of the Széchenyi 2020 program. The realization of this project is supported by the European Union, co-financed by the European Social Fund.

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