Semi-continuous casting of aluminium alloys

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Abstract. The target of our experiments is to simulate a complex production process under laboratory conditions. An industrial aluminium production line is examined using a semi-continuous casting device, running preliminary and trial experiments to find the optimal technological parameters for the physical simulation. Be the determination of the correct casting parameters the technological industrial process can be optimized.

1. Introduction
The semi-continuous casting technology has been known and used since the 19th century mainly for copper alloy production. In the vertical semi-continuous casting process the molten metal is fed from a crucible to the mould where it starts to solidify. The outer layer of the metal is solidified, while the inner part of still molten. The partly solidified geometry, the so-called strand can be drawn from the crystallizer, using additional cooling [1, 2]. During the solidification process, there are three phases in the system: liquid, semi-solid and solid [3]. The mould, where the metal shell solidifies is water-cooled, which is called primary cooling, while for strand is cooling using secondary cooling, which is usually a water spray [4]. Through the solidification process, numerous parameters are of key importance such as drawing speed and the intensity of the secondary cooling. The casting process can be only influenced indirectly, and the various parameters are all affecting solidification and must be aligned for the desired results. The melting- and solidification temperatures of the examined alloys, were determined using Thermo-Calc software, while the solidification characteristics were determined with NovaFlow&Solid software [5, 6, 7].

2. The semi-continuous casting device
As a part of a research, an Indutherm CC3000 semi-continuous casting device is installed in the laboratory of the University of Miskolc, which is mainly used for non-ferrous and precious metal casting. The target of the experiment is to create an experimental method to simulate the industrial process in a laboratory environment. By the help of the Induterm CC3000 casting device (Fig. 1) slabs can be cast with varying sizes [8]. In the device, the metal is melted by an induction heating unit in a graphite crucible.
Above the molten metal, the atmosphere can be vacumed or a protective atmosphere can be applied. Further parts of the melting zone are the inductor coil, the ceramic refractory, the thermocouples in the graphite crucible and the plug. The graphite plug is responsible for closing the crucible, having a 10 mm wide hole on its bottom, through of it the molten metal flows to a graphite mould surrounded by the water-cooled brass die. The temperature of the graphite mould cannot be controlled directly, but with changing the temperature of the molten metal, the drawing speed and the intensity of the secondary cooling.

3. Experiments

The experimental semi-continuous casting machine has not been used for aluminium casting so far and the main goal was to simulate the casting process of different aluminium alloys (Al99.5, AlSi, AlFe) which are used by the industrial process.

As the first step in the research plan, the exact compositions of the alloys were determined using inductive coupled plasma mass spectrometry (ICP). Based on the exact compositions, using the Thermo-Calc software, the temperature-dependent liquid phase ratio was calculated. The calculated curves are shown in Fig. 2. The Thermo-Calc software can be used to solve thermodynamic and kinetic calculations even for multi-phase systems. The base concept of thermodynamic equilibrium is, while the pressure, temperature, and composition are constant, the number, the ratio and the quality of the phases can be calculated minimizing the Gibbs free energy:

\[ G_m = \sum_{\phi} y_{\phi} \cdot \sum_{i} x_{i(\phi)} \cdot G_{m,i(\phi)} \rightarrow \min \]  

(1)

where \( G_m \) is the molar Gibbs energy (J/mol), \( F \) is the number of present phases, \( K \) the number of components, \( y_{\phi} \) is the phase ratio of the \( \phi \) phase, \( x_{i(\phi)} \) is the mole fraction of the component \( i \) in \( \phi \) phase, and \( G_{m,i(\phi)} \) is the partial Gibbs energy of \( i \) component in \( \phi \) phase [5, 9-10].

The casting experiments were carried out by pouring three different alloys: Al99.5, AlSi12.8%, and AlFe. Using the liquid phase ratio curves the melting and solidifying parameters of the alloys can be determined.

The second step of the research was the simulation experiments. The NovaFlow & Solid simulation software was used, running Control Volume method. By the help of the simulation mass and heat...
transfer in three dimensions can be calculated [6, 7]. The geometric model of the casting device was created using Solid Edge V20 CAD program. The created models were installed to the NovaFlow&Solid program where initial and boundary parameters were defined and the solidification was calculated as can be seen in Fig.3.

Four solidification cases were examined defining the melt temperature between 720-850 (°C). Parallel with the physical experiments 40 simulations were calculated to find the optimal casting parameters. With the help of computer modeling, the solidification time of alloys in the critical cross-section of the strand was determined, without drawing. In the case of 720 (°C) initial temperature the solidification time was 24 (s), while in the case of 850 (°C) it was 36 (s).

By the help of the physical and simulation experiments, the optimal casting parameters that can be used to reproduce the casting of the Al99.5 alloy were determined. The initial temperature of the last experiment was 850 (°C) which value was used later as the ideal graphite mould temperature.

If the temperature of the graphite mould is higher than 680 (°C) secondary cooling is necessary. To prevent overheating of the graphite mould the temperature of the water-cooled die was modified from 600 to 450 (°C). By the end of the experiment, the drawing speed and the secondary cooling intensity were set to the maximum value, which resulted in the best surface quality of the aluminium slabs [11].
4. Results

The Design of Experiments, which summarizes the technological parameters can be seen in Table 1.

| Parameters                              | Experiments       |
|-----------------------------------------|-------------------|
| Amount of poured alloy                  | 3 (kg)            |
| Protective atmosphere                   | argon             |
| Pressure of the protective atmosphere   | 1 (bar)           |
| Primary cooling                         | distilled water   |
| Primary cooling temperature             | 25-50 (°C)        |
| Primary cooling flow                    | 0.07 (l/min)      |
| Secondary cooling                       | water             |
| Primary cooling temperature             | 20 (°C)           |
| Primary cooling flow                    | 0.2 (l/min)       |
| Alloy                                    | Al99.5 | AlSi | AlFe       |
| Calculated liquidus temperature         | -      | 579.2(°C) | 648.3(°C) |
| Calculated solidus temperature          | -      | 573.1(°C) | 614.9(°C) |
| Solidification range                    | -      | 6(°C) | 33.4(°C)  |
| Pouring temperature                     | 850 (°C) | 770 (°C) | 840 (°C) |
| Crystallizer temperature                | 450 (°C) | 450 (°C) | 450 (°C) |
| Initial drawing speed                   | 0.3 (mm) | 0.3 (mm) | 0.3 (mm) |
| Initial pause                           | 3 (s)    | 3 (s)  | 1 (s)     |
| Drawing length                          | 4 (mm)   | 4 (mm) | 4 (mm)    |
| Technological pause                     | 9.9 (s)  | 9.9 (s) | 7 (s)     |

4.1. Solidification of Al99.5 alloy

The casting process started with the optimized parameters. The measured temperature of the graphite mould was not higher than 680 (°C), therefore the secondary cooling was not utilized. Based on the preliminary experiments, the initial drawing lengths was 0.3 (mm) with 3 (s) pause, which greatly reduced the risk that the metal solidifying prematurely and the strand tearing.

During the experiment, the drawing length was increased to 4 (mm) with a 9.9 (s) pause, which resulted in adequate surface quality. The optical microscope image of the Barker etched Al99.9 aluminium sample from the casted strand is shown in Fig.4. It represents the grain structure of the shell (finer) and the central (larger) strand parts. The experiment was repeated multiple times with the inspected technological parameters. The surface quality could be reproduced, which confirmed so that these settings are fixed to use for the Al99.5 alloy [9].

![Figure 4. The Barker etched microstructure of Al99.9 aluminium was investigated with optical microscope [9, 11]](image)

4.2. Solidification of the AlSi alloy

Using the Thermo-Calc software the melting point, 580 (°C), and the melting range, 8 (°C) of the AlSi alloy was determined. The melting range, like in case of Al99.5 alloy, is negligible, so the experiments started with the following initial values: liquid metal initial temperature is 770 (°C) and initial die
temperature is $450 \, (^\circ C)$. The initial drawing parameters were the same as in the case of Al99.5 alloy. During the casting process, secondary cooling was used. In this case, as well it proved to be true that for the successful casting the temperature of the graphite mould must be above the melting point of the alloy. The result was a product with exceptional surface quality. Fig.5. a) shows the casted AlSi strand and b) shows its Barker etched cross-section microstructure. The more and finer dendrites are in the shell part of the strand [9].

4.3. Solidification of the AlFe alloy
In the case of the AlFe alloy, the initial liquid metal temperature was $840 \, (^\circ C)$, while the initial die temperature was $450 \, (^\circ C)$. Based on the first results the casting parameters were optimized and for finally the drawing speed was set to $4 \, (mm)$ with a $7 \, (s)$ pause. With these settings reproducible and good surface quality was achieved.

It was proved to be true as well that the temperature of the graphite mould has key importance and has to be higher than the melting point of the alloy. Fig.6. a) shows the casted AlFe strand and b) shows its Barker etched cross-section microstructure. Its texture mainly contains dendrites, which is a primary solid solution.

![Figure 5](image1.png)

**Figure 5.** a) Casted AlSi strand b) Barker etched microstructure investigated with optical microscope [9, 10]

![Figure 6](image2.png)

**Figure 6.** a) The casted AlFe strand b) Barker etched microstructure investigated with an optical microscope
5. Conclusions
The target of this research was to simulate an industrial process under laboratory conditions. Based on the results of the experiments the optimal casting parameters can be determined for the Al99.5, AlSi and AlFe alloys. One of the importance of the results is, that this is the first time when the Indutherm CC3000 semi-continuous casting device is used for aluminium alloy casting. Additionally from the experiments, we could deduce the following results:

1. The Thermo-Calc calculations correspond to the values experienced during casting.
2. The NovaFlow&Solid software is capable to determine the time needs for the solidification of the metal in the mould which can be used for drawing time calculation.
3. In case of the examined alloys, the liquid metal must be overheated with ~190 (°C), while the temperature of the die, which responsible for the primary cooling, must be set to 450 (°C).
4. To prevent surface flaws, additional to the optimal liquid metal and die temperature, the drawing speed has key importance. In case of the AlSi alloy, the ideal value is 4 (mm) drawing with 9.9 (s) pause.
5. In case of higher drawing length, the leakage of the liquid metal can be avoided using longer pause and secondary cooling.

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