INTRODUCTION

Each year, approx. 400 million tons of blast furnace slag is produced worldwide with a tapping temperature of around 1,500°C. Currently, the slag is granulated in wet granulation plants using large volumes of water and to date it has not been possible to utilize the remnant heat energy of the molten slag, with approx. 1.7 GJ of energy per ton.

However, in an R&D project currently underway by a consortium of companies led by Primetals Technologies and comprising voestalpine Stahl GmbH (Austria), FEM Building Materials Institute (Germany) and the Montanuniversität Leoben (Austria), a dry atomizing technology is being developed to use air to cool molten slag and recover the lost heat energy.

Phase 1 of the project has been completed where a technical plant was set up in 2012. The research results have shown the process suitability as an industrial application and the decision was taken to proceed ahead with the project to Phase 2 to install a semi-industrial scale pilot plant. [4]

The design and erection for Phase 2 pilot-plant at the site of voestalpine Stahl in Linz has been finished in May 2017 followed by a intense commissioning phase. Since June 2017 discontinuous batch campaign operation are executed to gain know-how and allow for process optimization for later commercialization of the process. This paper summarizes the major results until January 2018 and outline further development work required to achieve industrial readiness.

DRY SLAG GRANULATION BACKGROUND

Slag sand as a cement clinker substitute
Traditional production of cement clinker from limestone, sand, clay and other components requires a high-temperature process (around 1450°C) in a rotary kiln. Beside the high demand of raw materials the process is also associated with significant primary energy demand and high specific CO₂ emissions. The substitution of cement clinker by blast furnace slag sand is an attractive economic alternative for the cement industry, because it reduces energy costs and improves the carbon footprint remarkably. Approximately 1 ton of CO₂ emissions can be avoided for each ton of clinker substituted by slag sand (primary energy saving plus the CO₂ which is chemically bound in the limestone).

Wet Granulation State-of-the-Art for the Production of Slag Sand
In this case the slag is quickly "quenched" in granulation facilities using large quantities of water, producing a fine-grained, amorphous but also wet product, known as slag sand. Due to the amorphous structure, the slag sand when ground to cement
additive fines, form hydration products in conjunction with water (latent hydraulic behavior). These products essentially correspond to the hydration products of Portland cement clinker, the main component of Portland cement. The key prerequisite for the use of slag sand as a binding agent in the building material industry is thus satisfied. Therefore, approximately 80% of blast furnace slag sand is used as cement additive. The added value as cement additive is usually than utilizing the slag as aggregate material for road construction.

The wet granulation process operates with a high water to slag ratio of about 8:1. The advantage of the wet process is that it is accepting wide fluctuations in the mass flow and physical/chemical properties of the slag. However, the wet process faces also significant disadvantages:

- Despite mechanical dewatering in drums, silos or heaps, a residual moisture of about 10 - 12 % remains in the slag sand. For the manufacturing of cement, the product therefore first has to be dried, which requires substantial energy input of more than 100 kWh per ton of slag.
- For granulation with open water circuits, vapor stream containing sulphur with intense odor are released, and a correspondingly large amount of fresh water (about 1 m³/t) has to be fed into the system. Granulation plants with closed water circuits and condensation systems can largely prevent such emissions of water vapor containing sulphur, but are also capital intensive.
- When slag is quenched with water, the high energy potential of the hot liquid slag is wasted (heating and evaporation of water).
- For granulation, the circulated water has to be re-cooled in cooling towers or with other cooling methods. Mainly cooling towers are equipped with electrically powered fans and also the cooling water circulation system are consuming significant electrical power. Finally the heat is released to the environment at a low temperature level without any chance to be utilized.

**Dry Granulation - Leap-frog Innovation for the Production of Slag Sand with efficient Energy Recovery**

Intense water consumption and energy for drying can be avoided by dry dispersion and quick air cooling of the liquid slag. The essential point for any dry technique is that the obtained slag product meets the properties as cement additive. Basically the target is to achieve at least the quality of wet granulated slag sand. This applies in particular to the glass content (target > 95%), which is a key parameter for the latent hydraulic reactivity and hence the quality of the slag sand.

The glass content has a direct impact on the strength of the concrete. However, the required glass content can only be achieved by ultra-fast cooling below the transformation temperature. Due to the less efficient cooling mechanism of water-free air quenching, the dry process is technically more challenging than conventional water based granulation.

![Figure 1: Dry Slag Granulation (DSG) Concept](image)
Dry slag granulation is based on molten slag atomization using a variable speed rotating cup or dish (see Fig. 1). The slag is fed from the slag runner via a vertical refractory lined pipe directly onto the center of the rotating cup. The rotation of the cup accelerates the slag and forces the slag outwards to the cup lip where it is atomized (see Fig. 2).

Diameter and shape of the cup has significant impact on the quality of the slag atomization process functionality at different process. Variable speed control has to maintain the fluctuating slag flow and properties. By applying CFD fluid analyses for the rotating cup, parameters of slag layer thickness & slag velocity vectors were evaluated for different load conditions and cup designs. These results were combined with the extensive operation experience from the dry slag granulation pilot plant to define a proper cup design. The speed of the cup is varied according to the current slag conditions (e.g. flow, temperature) to reach a consistent product quality (e.g. grain size distribution, glass content) and process stability.

The atomized particles, mainly in a grain size range of 0.5 to 3 mm impact on an inclined water cooled wall, bounce off the wall and falls into a bed of granules. A first particle cooling effect is caused mainly by the radiation to surrounding equipment and product, and convection heat transfer to the cooling air during the flight phase towards the water cooled wall and finally to the granulate slag bed. Part of heat transfer takes place at the water cooled wall by conductive heat transfer.

Small sized particles have already created a solid surface before impacting the water cooled wall and bounce directly off the water cooled wall without deformation. Larger sized particles cannot create a stable solid crust on the particle surface during their first flight phase. They are deformed when impacting the wall to flattened form, but they re-establish a spherical shape again after the wall impact due to the physical properties of blast furnace slag. The correct hitting angle, the material quality of the impact surface and the cold surface temperature of the water cooled wall prevent sticking effects of the slag particles on the side wall elements.

The solidifying granules fall into a bed of granules. The cooling air introduced into the granulate bed by several different air supply chambers flows through the bed. The active control of the different cooling air flows into the cooling air chambers ensures that the granulate bed remains in stable condition. The resistance time of the granulate in the bed is defined by the required heat exchange time between granulate and cooling air. Major part of heat transfer in the granulator takes place in the granulate bed.

The discharging system at the bottom of the granulator is designed for independent discharge of granulate from the granulate bed to a conveyor system. Cooling air can pass the discharging modules to have a direct bottom up flow of the cooling air in the granulate bed / granulator (counter flow principal).

Obviously “dry” granulation requires no subsequent drying of the product. This leads to a CO\textsubscript{2} reduction potential of about 30 kg per ton in comparison with wet process. Given global slag sand production of approximately 210 million tons of slag sand (2007), this equivals to a potential CO\textsubscript{2} reduction of more than 6.3 million tons per year.
PHASE 2 - DRY SLAG GRANULATION PILOT PLANT

With environmental and energy saving considerations becoming ever more important and even becoming enshrined in legislation, there is clearly a need for a major improvement in slag handling. Our past experience of the dry granulation process is being further enhanced with heat recovery technology to satisfy this requirement and the topic is now a major R&D project at Primetals Technologies in conjunction with the consortium partners. voestalpine Stahl GmbH Linz site has been chosen to build a new semi-industrial scale dry slag granulation pilot-plant which will be capable of handling slag flow up to 2 tons per minute from a single tap hole in STEP 1. This STEP will assess and improve process performance and evaluate detailed off gas parameter information for a subsequent heat recovery plant installation. If the STEP 1 plant operation will be successful it is the intention to upgrade the facility in a STEP 2 development to treat full slag flow from multiple tap holes on the blast furnace A and install downstream a waste heat recovery plant.

Phase 2 Pilot Plant Process
The aim of the pilot-plant is a long term slag granulation test at first time with slag flows close to industrial plant sizes. In following figure a simplified flow sheet with the principle function of the STEPl pilot plant is shown:

![Figure 3: Process scheme of Phase 2 STEPl pilot-plant installation at voestalpine Stahl Linz](image)

Main focus is on the core process – the rotating cup atomization process. But also several other equipment’s at the pilot plant have to be tested intensively regarding their reliability for a dry slag granulation process. A closer look the key areas of the dry slag granulation pilot plant is outlined below:

**Process Air Supply**
A radial fan is installed to supply the granulator and the various air cooling chambers with process air. Based on the thermal balance of the granulator an air amount of maximal 180,000 Nm³/h is provided to cool the granules down to target temperature. This air amount and the foreseen maximum pressure drop in the granulator – mainly caused by the granulate bed - requires a fan power of 1.5 MWel. The air flow in the different air chambers can be controlled individually to allow for the required air distribution and granulate bed conditions.

**Process air outlet / Off gas**
Target temperature of the process air off-gas is 560°C. One focus of the test campaigns at the pilot plant is to maximize this off-gas temperature, detecting the limits of the process, but still fulfilling the slag product requirements. The air exiting the granulator is de-dusted by 2 parallel cyclones to meet the environmental emission levels.

**Slag Supply**
The slag is fed to the granulator via a slag runner which is directly connected to the blast furnace tap hole. Based on the fact that the blast furnace slag tapping flow will exceed the granulator capacity, the slag flow is limited to a specific flow level applying refractory slag divider. Just before the slag entrance into the granulator the slag can be diverted to a slag emergency pit in case of an emergency shut down of the granulator.
Granulation process
The core equipment – the rotating cup unit – is fed with slag from the top. It is possible to equip the granulator with different rotating cup configurations for process optimization of the rotating cup design. The speed of the cup is actively controlled within a certain speed range. Several visual high-speed and temperature imaging devices are installed for monitoring, control and evaluation of the granulation process. The particles impacts an inclined water cooled wall. The main inner diameter of the granulator is about 6.5 meter. The bottom of the granulator forms the granulate bed with a filling weight of about 30 tons. The bed is intensively cooled from the bottom and side walls with cooling air properly distributed.

Discharge System
The core equipment of the discharge system is a wide area discharge module. With this system a controlled discharge of granulate at the bottom of the granulator in combination with a wide area cooling air supply is possible. The granulate is discharged from the center of the granulator with 2 conveyors and stored in a granulate pit area.

![Figure 4: View at the dry slag granulation pilot plant (East & West)](image)

![Figure 5: View at the dry slag granulation pilot plant (East)](image)

Phase 2 Pilot Plant Operation
The phase 2 pilot plant was started-up in June 2017 and operates since then in short campaigns. Several hundred tons of BF slag has been granulated during the first half year of testing.

Plant preparation:
Before starting the operation of the plant the main operation parameters are defined accordingly. One important parameter is the maximum amount of slag flow that is guided to the granulator. The slag flow to the granulator will then be restricted to the defined amount. The surplus of slag is guided to the existing slag handling system. Before start of tapping of slag from the blast furnace runner to the pilot plant is pre-heated. Before The granulation plant is set-up to stable condition, this means all systems are running (spinning of rotating cup, process air, water cooling circles etc.) with a main focus on the stable conditions of the granulate bed. Then the slag is fed continuously to the granulator.
**Plant operation:**
From first slag feeding into the granulator it takes about 15 minutes to achieve stationary process conditions and to allow to evaluate the big data from DSG operation. All components in the granulator and the fluidized bed has to heat up until they reach their final temperature (if constant slag flow is given). Based on the indication of process parameters and the visual monitoring of the granulation process following main parameters will be adjusted during the trial:

- Speed of the disc
- Amount of process air and its distribution to the granulator
- Activation (or deactivation) of the granulate discharge from the granulate bed

It is the aim to run the granulation process during the whole tapping until the active tap hole at the blast furnace will be closed again. Only in case of emergency condition the granulation process is interrupted by diverting the slag flow towards the emergency pit.

**Analyses of operation:**
After every campaign the granulator is carefully inspected with main focus on:

- Effects of wear in the granulator (especially at rotating disc)
- Amount of granulated solidified slag
- Environmental parameters, energy & mass balance, off-gas parameters, etc.

All recorded measurement data of each trail are systematically analyzed. In the following table typical main parameters of a granulation trial are described (parameters at stationary operation conditions):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Slag Flow</td>
<td>30-40 [ton/hour]</td>
</tr>
<tr>
<td>Duration of granulation</td>
<td>~60 [min]</td>
</tr>
<tr>
<td>Granulated slag</td>
<td>30-40 [ton]</td>
</tr>
<tr>
<td>Temperature of fluidized bed / granulate discharging temperature</td>
<td>~200 [°C]</td>
</tr>
<tr>
<td>Total process air flow</td>
<td>~170,000 [Nm³/h]</td>
</tr>
</tbody>
</table>

Figure 6: Typical main process parameters of a granulation trial

Based on the recorded process data an energy- and mass balance of the granulator is established. This is an important information to adjust the slag flow online via a slag flow evaluation and control systems. A typical energy balance of a granulation trial can be seen in following figure:

Figure 7: Thermal power balance of a typical dry slag granulation trial
Granulate product:
Requirement for starting the granulation process is a stationary established fluidized bed inside the granulator. Then the slag is granulated for about one hour and the granules are collected in the granulate bed. The analyses of the slag product shows 97 to 99% glass content. These values are equal or better compared to conventional wet granulated slag. First investigations on concrete properties have shown appropriate values compared to the wet granulated slag. There is no doubt that product quality with the dry slag granulation pilot plant as required can be achieved. Extensive large scale cementitious testing are on the way and will be reported later.

Results and Outlook:
The current status of development at the dry slag granulation pilot plant confirm that a stable granulation for a slag flow of up to 40 tons per hour can be achieved. Following main development steps are scheduled for the up-coming months:

- Increasing the maximum pilot plant slag flow capacity up to 60 tons per hour
- Testing of pilot plant process limitation for achieving a maximization of off-gas temperature
- Long-term granulation experience to detect wear and sticking behavior at potential critical plant components

CONCLUSIONS

Liquid blast furnace slag represents the largest untapped high temperature waste energy source in the iron and steel industry. The consortium partners voestalpine Stahl GmbH, FElS Building Materials Institute and the Montanuniversität Leoben, Primetals Technologies have decided after successful lab-scale phase 1 during 2013-2015(40 kg/min) to enter into phase 2 and to install a semi-industrial pilot plant. Engineering, manufacturing and installation was finalized in May 2017. Since June
2017 the pilot plant is operated in batch campaigns. During the first six month the focus was on process optimization and operation know-how collection. Process control parameters have been developed and implemented. A couple of hundred tons of slag product has been granulated. The quality of the product shows high glass content of 97% plus. Cementitious parameters show appropriate values. During the next month the focus will be on big data gaining, improve process control, process reliability and determination of wear and sticking.

The benefits of the dry granulation process were confirmed and are significant.

Would only half of the operating blast furnaces switch from wet to dry type granulation, more than 3.5 million households can be supplied with sustainable power or 6.5 million e-cars can be charged on basis of 10000 km per year driving.

The additional advantages for cement producers are to utilize a first class cement clinker additive which is dry, highly glassy and easy to handle and at remarkably reduced carbon foot print. makes this a very good fit with our overall customer’s needs.

The development and operation of the dry slag granulation pilot plant at the site of voestalpine Stahl in Linz is bringing the dry slag granulation technology one step closer to industrial commercialization.

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REFERENCES