Forced air granulation of secondary metallurgical slag

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Dalmine S.p.A. (Tenaris S.A.) tested a pilot plant for Secondary Metallurgy Slag (SMS) valorisation as a raw material. The purpose of the test was to recovery CaO (lime), which is approximately 55% of the total SMS slag stream. The industrial process have been developed and designed in collaboration with Tenova S.p.A, the detailed slag characterisation performed by Rina-CSM S.p.A while the introduction of obtained product in different markets evaluated by the Politecnico di Milano.
The process consists in the fast cooling of the liquid SMS slag mixed with residual steel by forced air stream during slagging to allow their rapid solidification.
The paper describes the testing facilities, the set-up of multiphase simulation model and the experimental results along with theoretical background.
The performed tests prove that air granulation process of SMS slag in liquid phase will minimize the associated environmental impact, significantly increases workers safety and gives the basis for targeting at the installation of the full-scale prototype within 2020. Industrialization of this process will allow full recovery of residual steel and reuse of the SMS slag within the EAF process or as by-product with a number of potential applications and significant market value. Detailed analysis of the potential commercial applications for granulated slag is ongoing.

KEYWORDS: AIR GRANULATION, LF SLAG, LF SLAG STABILIZATION, SECONDARY METALLURGY, CaO RECOVERY

INTRODUCTION

Circular Economy is a challenging, though vital, strategy for the 21st century. This philosophy reshapes steel industry thinking about resources and production, where waste is no longer waste but a secondary resource, a crucial part of a sustainable material's life cycle. This require redesigning some of present practices to avoid waste being landfilled (1).
The European steel industry generate about 21.4 million tons of slag in 2014. About 24% is not being reused, representing a severe environmental problem in Europe, but also a huge amount of available material for potential recycling (2).
In particular, Ladle Furnace (LF) slag (also known as white slag, secondary refining slag or SMS) handling currently represents a significant safety, environmental, operational and financial concern for EAF steel production (3). Ladle furnace slag is produced in the so-called secondary metallurgy process, representing the final stages of steelmaking where the steel is desulfurized in the transport ladle. The most important functions of the secondary refining processes are the final desulfurization, the degassing of oxygen, nitrogen, and hydrogen, the removal of impurities. At the end of the casting process, SMS handling and post-processing represents a significant part of typical operations. Slag handling differs by site based on environmental legislation, available space, and site location (4).

The common slag handling process at the TenarisDalmine site consists of collecting SMS in slag pot, dumping it onto the ground for the slow cooling by natural air convection, and then separating steel from slag by mechanical operation. Eventually, the recovered steel is recharged in the EAF while the SMS slag is sent to waste recovery plants. Slag handling is a highly time-consuming operation and generate significant amount of dust (5), that today requires water spray in the slag pit in order to reduce it. The water used increases plant water demand and the weight of final material that is sent to recovery plants or landfilled as waste. Lastly, all the operations associated to SMS slag handling (transportation, separation, loading etc.) represent a significant safety and operational risks.
Dust emissions, energy consumption, environmental footprint and safety risks can be avoided with a new

technology that overtakes the traditional slag-handling methods, while the associated costs are eliminated by the sale of the obtained byproducts.
Among the different alternatives (6), forced air granulation of secondary metallurgical slags represents for TenarisDalmine the most appropriate and more promising way to manage SMS.

TenarisDalmine tested a pilot plant for SMS valorisation as a raw material. The purpose is to recovery CaO (lime), which is approximately 55% of the total SMS slag stream (**Tab. 1**).

Tab. 1 - Chemical analysis before granulation.

CHEMICAL ANALYSIS		
CaO [%]	Al_2O_3 [%]	SiO_2 [%]
40-60	15-30	5-15

In summary, dry granulation of SMS slag allows an environmental friendly and sustainable subsequent processing for one of the last issue in the modern EAF steel manufacturing route.

The use of these alternative materials helps to minimize primary materials mining, i.e. saving natural resources and protecting the landscape.
LF slag can be used in many different areas such as soil stabilization, as fertilizer, reused in EAF as lime, production of cement and concrete, filler for asphalt and so forth (7).

DEFINITION OF THE TEST RIG

It is well know that secondary metallurgy slag during solidification passes through different phase. During the cooling down of the ladle, the slags first changes to β-C_2S at 630°C, and then changes in γ-C_2S at temperature lower than 500°C. The β-γ conversion is accompanied by 10% volume increase, resulting in the slag shattering into powder because of their different crystal structures and density.
As reported in (8), it is proved an interconnection between the cooling rate and the stabilization of the slag. Laboratory tests demonstrated that a cooling rate of at least 5 °C/s is required for slag structure stabilization.

Therefore, two important aspects should be considered in order to define the test conditions: the target size of granulated materials and the cooling rate.
The ratio between gas and slag flow rate (GSR) represent a critical design element. Literature (9) reports that optimal GSR values for the granulation process are between 0.5 and 2, with a gas speed between 40 m/s and 120 m/s. Higher GSR leads to smaller particles size, increasing also the production of significant fiberglass, while smaller GSR make the granulation process more difficult, leading to bigger particles with significant agglomeration phenomena.
Granulometry is strictly related to the air velocity and to Weber number that is function of the gas characteristics and slag properties (10,11).

In order to verify the key parameters and the feasibility of the LF slag granulation an industrial-scale air granulation system is built in TenarisDalmine. This system consists of a simplified equipment (***Fig. 1***) that allows testing the key design principles of the full-scale air granulation system.

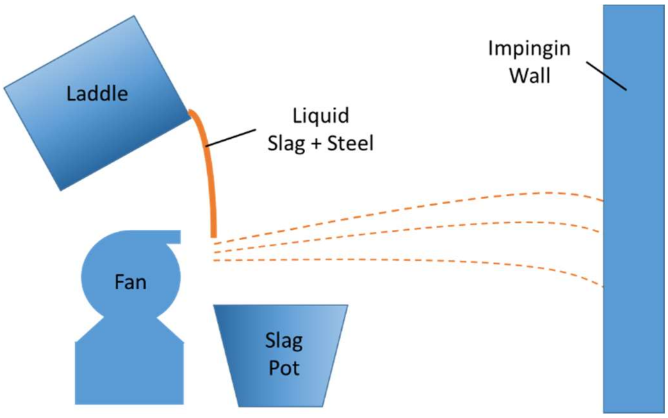

Fig. 1 - Schematic representation of the test rig.

During the test, the ladle tilting is controlled manually from the EOT crane. For safety reasons, the SMS slag is poured over the slag pot to avoid falling of liquid slag and steel on the floor. Granulation is obtained by air blowing with a dedicated industrial fan. A metal screen is positioned at a distance where the slag is expected to be complete solid. The granulated slag was collected on the floor.
Slag and air flow rates are settled in order to ensure a correct GSR during the entire test.

INDUSTRIAL TEST

Two tests campaign were performed. The first test was performed at GSR of 0.15 and as shown in the ***Fig. 2*** only a portion of slag was granulated, while the remaining part fell into the slag pot. This because the value of GSR was below the range mentioned above.

Fig. 2 - First test of air granulation process.

The second test was performed with a GSR of 0.5. As expected, a higher portion of slag was granulated (see **Fig. *3***). The critical aspect is that the trajectory of the granulated slag was not high enough for passing over the slag pot upper edge. This is the main reason why the granulated slag collected on the floor was not the 100% of the poured slag.

Fig. 3 - Second test of air granulation process.

In both conditions, during the test no dust was produced and only a very limited quantity of fiberglass was observed.

GRANULATED SLAG CHARACTERIZATION

After rapid cooling due to air granulation, the slag appeared granular and vitreous (**Fig. *4***). The sample collected was characterized in terms of grain size distribution, magnetic fraction, chemical analysis and X-Ray Diffraction (XRD).

Fig. 4 - SMS slag after rapid cooling.

Fig. 4 shows the grain size distribution of the SMS slag after rapid cooling. Coarse fraction is between 9-40 mm. For the material between 2.8-10 mm (***Tab. 2***) both the magnetic and the slag fraction were recovered, and reported in ***Tab. 3***.

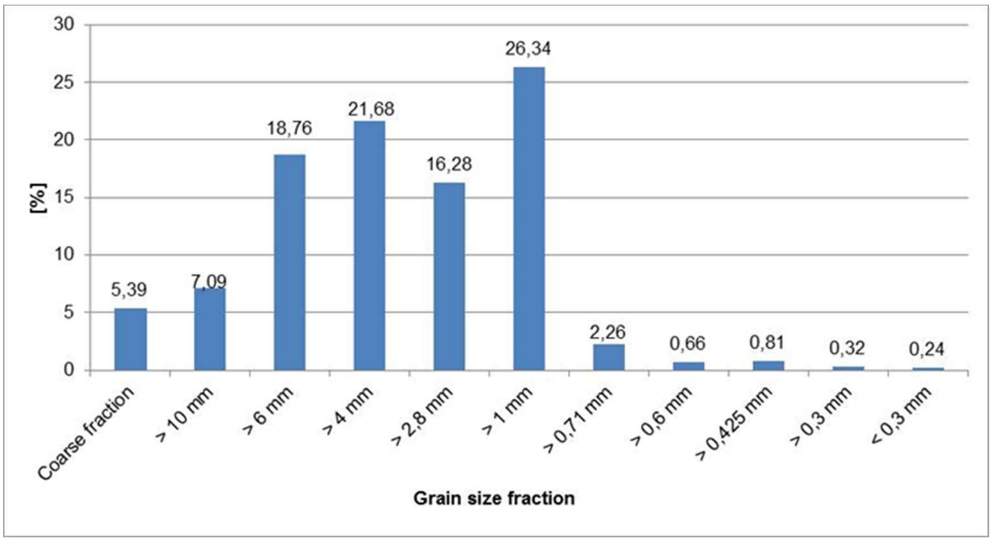

Fig. 5 - Grain size distribution of SMS slag after rapid cooling.

Tab. 2 - Amount of magnetic fraction for the material between 10 and 2.8 mm.

Grain size fraction			
>10 mm [%]	**>6 mm [%]**	**>4 mm [%]**	**>2.8 mm [%]**
0.94	4.70	4.73	1.68

Tab. 3 - Chemical analysis of slag and magnetic fractions for the fraction 10-2.8 mm.

CHEMICAL ANALYSIS								
	Fe_2O_3 [%]	**Al_2O_3 [%]**	**SiO_2 [%]**	**MgO [%]**	**CaO [%]**	**Cr_2O_3 [%]**	**MnO [%]**	**TiO_2 [%]**
Slag	0.78	23.1	7.58	5.68	58.9	<0.05	0.12	0.49
Magnetic	27.28	18.18	6.07	4.78	34.56	1.32	0.35	0.30

Slag is made of four main oxides (Al, Si, Mg, and Ca) while the magnetic fraction is mainly made of Ca and Fe oxides.

In general, steel slags chemical and phase composition is very variable due to different facilities in which they originate and due to variability of produced steel alloys. The portion of crystalline phases and glass phase also depends on cooling rate of melted slag. In the SMS slag the crystalline phase contains mainly dicalcium and tricalciumsilicate, responsible of dust formation due to the phase modification during a slow cooling. The XRD has been used to indentify the glass phase of the slag produced during the test. For this purpose, sample of slags with grain size below (dust) and above (coarse) 0.71 mm were analyzed. **Fig. *6*** and **Fig. *7*** show the results.

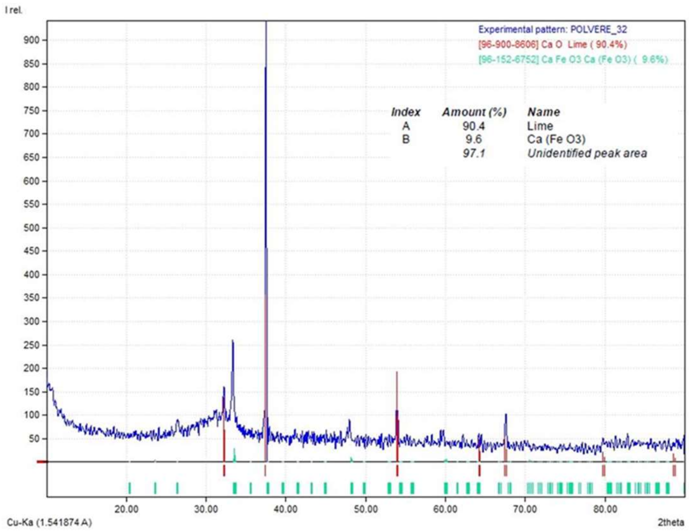

Fig. 6 - XRD of dust fraction below 0.71 mm of SMS slag after rapid cooling.

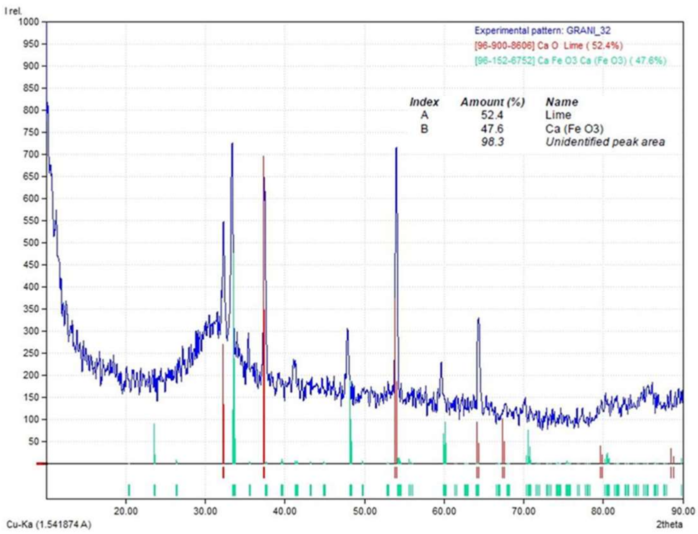

Fig. 7 - XRD of dust fraction above 0.71 mm of SMS slag after rapid cooling.

An unidentified peak area In the glass phase XRD analysis is present, while the peaks of the different species are clearly visible in the analysis of the crystalline phase. For this reason, when only crystalline phase is present, the base line is flat, allowing a quantitative analysis of the species.

In both samples of this slag, the main phase (more than 90%) is glassy, while the rest of the sample is of a crystalline phase in which the principal specie is lime. This shows that the cooling process used in these industrial trial transformed the slag in a glass material without dust formation.

CFD SIMULATION

A 3-D Computational Fluid Dynamic (CFD) model was developed in order to obtain qualitative information about the test and guide the design process. In this way, it is possible to better understand the phenomenology of the granulation process without performing too many full-scale tests.

Model Description

The granulation process is modelled using multiphase models available in the ANSYS FLUENT framework (12), while slag and steel are modelled as solid materials.

Gas phase is modelled by Time Averaged Reynolds Navier-Stokes equations. Air is described as a non-reacting ideal gas with temperature-dependent thermo-physical properties. Turbulence is taken in consideration by means of the standard k-ε model, a two-equation semi-empirical model based on the transport equations for the turbulence kinetic energy k and the dissipation rate ε (12). Wall-fluid interactions are described with a wall-function approach, based on the standard wall-function of the k-ε model.
Slag and steel are considered already solid particles, after the break-up of liquid slag and steel with a distribution obtained from the experimental trials. This approach represents a strong simplification but has been considered the best compromise between accuracy and computational time avoiding computationally-expensive approaches (like Volume of Fluid) while the most representative phenomena of the system are taken into account.

Solid phase is described by means of a Discrete Phase Model (DPM), where the fluid dynamic field interacts with two different materials (i.e. the slag and the steel). To better describe the thermal interaction with the fluid phase, thermal properties of slag and steel are described by means of temperature-dependent correlations, taking into account also the solidification process.
Due to the high temperatures, the radiation is also taken into account by means of a DO model.
The test rig is described as a 3-D domain, ranging from the fan outlet up to the impinging wall (**Fig. *8***).

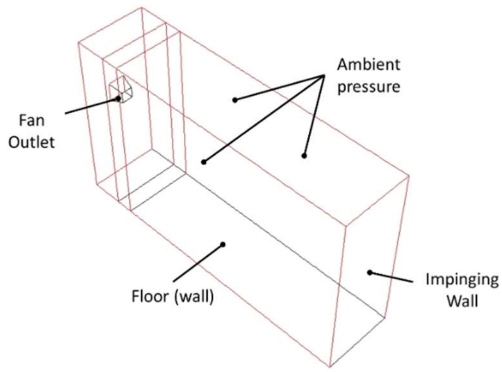

Fig. 8 - System geometry and boundary conditions.

An ambient pressure condition is imposed all around the domain, except for the walls represented by the fan, the floor and the impinging surface, which are described as surfaces where convection phenomena occurs.

Model Results

The CFD model was first validated against the particle trajectories as a function of the GSR. In particular, it is possible to observe that with a GSR equal to 0.15 (**Fig. *9***) the particles tend to accumulate very close to the pouring point (identified by the surface B in **Fig. *9***) rather than impinging on the desired vertical surface (plain A in **Fig. *9***) they. On the other hand, **Fig. *10*** shows that a GSR of 0.5 produces trajectories that lead the particles to imping on the vertical surface. Both cases show a good qualitative agreement between the experiments and the simulations.

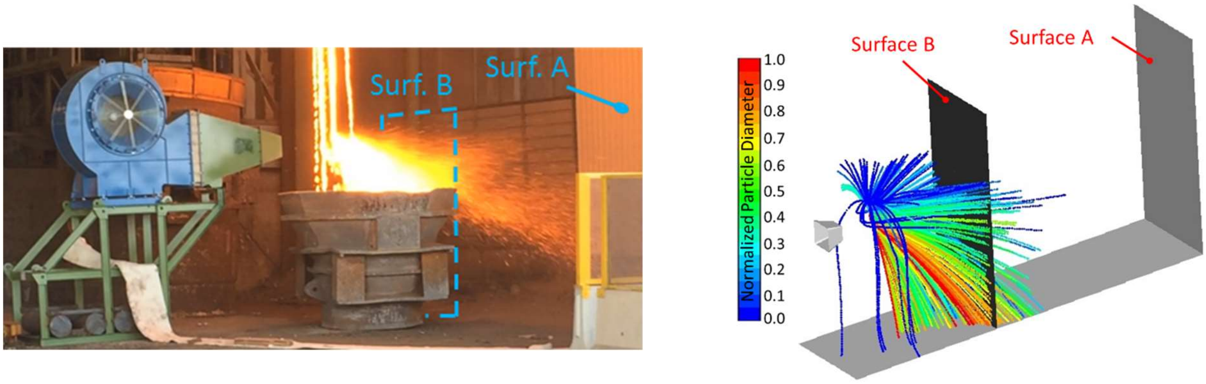

Fig. 9 - Comparison between experimental (left) and simulated (right) particle trajectories with GSR=0.15. Surface A represents the impinging wall, while surface B the limit of the pot used in the experiment. Trajectories in the simulation are colored by non-dimensional particle diameter.

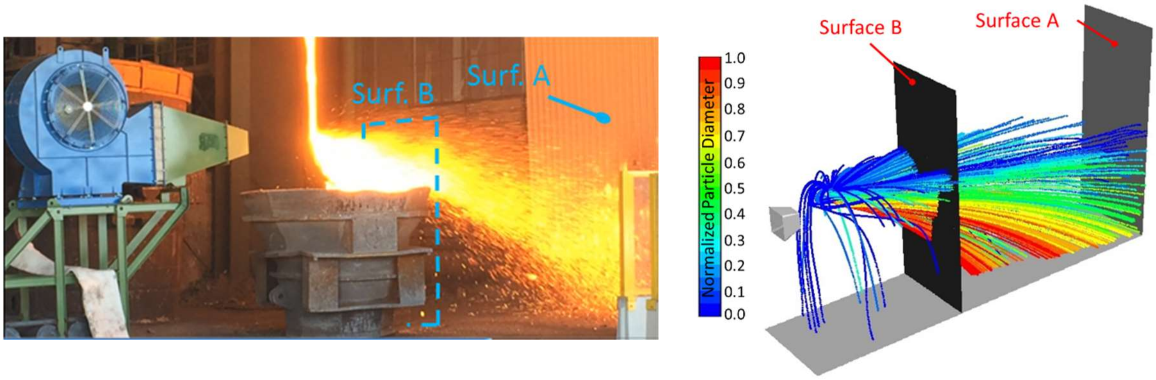

Fig. 10 - Comparison between experimental and simulated particle trajectories for GSR=0.5. Surface A represents the impinging wall, while surface B the limit of the pot used in the experiment. Trajectories in the simulation are colored by non-dimensional particle diameter.

Fig. 11 highlights the importance of using a coupled model to represent the interaction between the solid and the gas phase. When these interactions are taken into account (**Fig. 11** panel B) the gas flow deviates when it impinges on the slag. In this way, the gas phase transfers part of its momentum to the solid particles, resulting in the dispersion pattern observed in **Fig. *10***. On the contrary, this phenomenon does not occur when the coupling between gas and solid phase is neglected (**Fig. 11** panel A), leading to a dispersion pattern that does not match the experimental observation.

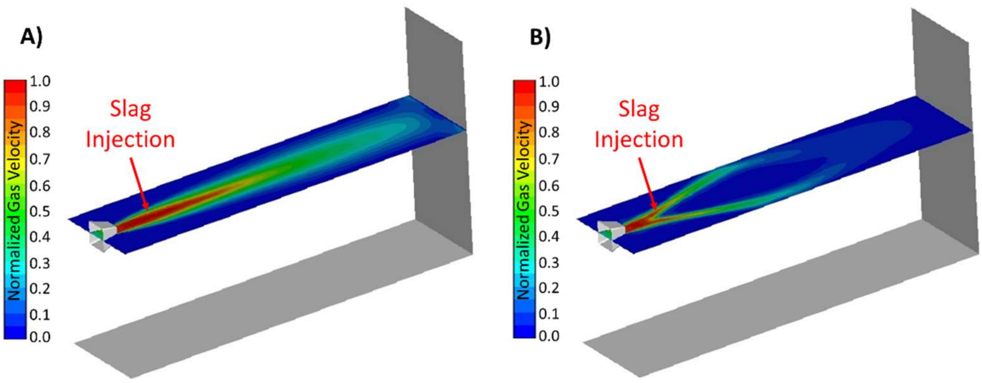

Fig. 11 - Effect on the gas flow field of the interaction between solid and gas phase in the calculation. Panel A: without gas-solid interaction; panel B: with gas-solid interaction.

The model shows a very high cooling rate (around 900 °C/s), which is much higher than the 5°C/s required to stabilize the LF slag and avoid the β to γ phase transformation. This is in line with the observed glassy/amorphous structure of the experimental trials.

In order to reduce the amount of slag poured in the pot, a new configuration was also proposed. In particular, as showed in ***Fig. 12*** the fan outlet is tilted upward of 15 degrees and moved back, with the aim to increase the particles flight time. Moreover, the pouring point is moved closely to the fan outlet, in order to intercept the air with the higher momentum.

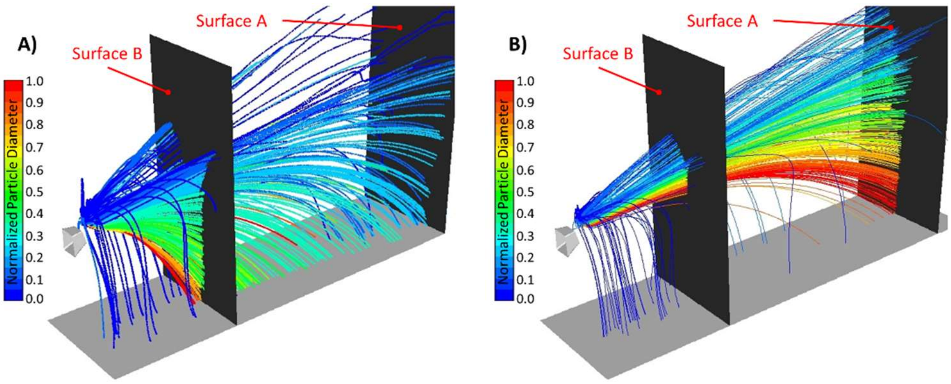

Fig. 12 - Particles trajectories with the new fan configuration. Panel A: GMR=0.5; panel B: GMR=1.6. Trajectories are colored by non-dimensional particle diameter.

As can be observed in ***Fig. 12*** panel A, the new configuration is not sufficient to achieve the goal of reducing the slag going in the pot with a GSR of 0.5. However, an increase of the GSR is required, as showed in panel B of ***Fig. 12*** (GSR=1.6).
Additional industrial experiments with new configurations and GSR are foreseen, in order to confirm the expected feasibility of the granulation process.

CONCLUSIONS
Air granulation technology offers an improved way of handling LF slag compared with the existing industrial practice. Preliminary results from full industrial tests performed at the Tenaris steelshop located in Dalmine demonstrates that air granulation is technically feasible allowing several advantages:

- **Resources conservation**: 25.000 ton/y of SMS slag will be treated resulting approximately in 13.000 tonCaO/y recovered just for the Dalmine S.p.A. plant. The application of this technology to the EU will allow the saving of 1.56 MtonCaO/year. This calculation is based on the hypothesis that the annual production of steel slag in EU27 is of 21.8 Mton/y and 13% of it is SMS slag (13)). This represent roughly 5-6% of the EU annual lime production (with the hypothesis of a European lime production of 28 Mton/y (14)). Standard lime production (calcium carbonate decomposition) requires almost 2 tons of $CaCO_3$ for every ton on CaO produced. Therefore using SMS slag for lime production instead of $CaCO_3$ will:
    - avoid environmental impact from raw material ($CaCO_3$) extraction
    - avoid air pollution due to dust production and product transportation
    - preserve the landscape

- **Energy saving potential**: SMS slag already contains CaO hence the reaction of calcium carbonate decomposition is avoided, resulting in the saving of 0.89 MWhth/tonCaO (with the hypothesis of calcium carbonate decomposition ΔH°R=179 kJ/mol, MMCaO=56 g/mol). This technology will allow the saving of 11.5 GWhth/y just for Dalmine S.p.A and 1.388 GWhth/y for European application.
- **GHG emission saving potential**: using SMS slag for Lime production will avoid the production of approximately 1 $tonCO_2$/tonCaO. Dalmine S.p.A. will avoid the production of 13 $ktonCO_2$/y and the

European application will result in the saving of 1.56 MtonCO_2/y.

Additional industrial experiments with new configurations are foreseen in order to verify the flexibility of the process and obtaining guidelines for the design of the industrial facility overcoming the remaining technical challenges. Moreover, detailed analysis of the potential commercial application for granulated slag is ongoing. The goal is the installation of the full-scale industrial prototype within 2020.

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