Advanced vision systems to control ladle slag carry-over

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Summary
Ladle deslagging operation in metals production is a process with manual control and no registration of process data. This results in process variations that influences on stability and efficiency of the subsequent processes as well on product quality.
A vision system monitoring the ladle deslagging area, LadleSlag, has been developed and introduced at a European steelmaking facility in order to continuously analyze and measure the slag surface area coverage.
The obtained information – a measured value and images of the end result – are used to assists the operator in reaching the process objectives. In addition, information is saved in databases for process traceability and development purposes.
The present paper elaborates on the importance of limiting the slag carry-over variation and presents some selected observations from the use of LadleSlag in steelmaking operations.

Key Words
Ladle, deslagging, slag removal, slag carry-over, process stability, production stability, reoxidation, non-metallic inclusions, metal losses, metal yield, image analysis, vision system, steelmaking, metal production.

Introduction
It is generally known that slag carry-over has influence on the subsequent processing and product quality, but few has really given it an effort to bring it under control. In the strive to produce higher and more uniform product quality it is now time to target the deslagging operation following the principle “what you see, you can measure, and what you measure you can control”.

Ladle deslagging operations

The last unknown
Considering the impact of slag carry-over on processing stability, product quality and production economics, as discussed further below, it is somewhat surprising that the deslagging process is performed without any instrumentation or operator support systems.
Previous studies show that the variation between heats is higher than acceptable and may range 5-90% surface coverage after finished operation[1]. In the world of liquid metal processing ladle slag carry-over stands out as one of the last unknowns.

Steelmaking operations and deslagging
In steelmaking the use of ladle deslagging operation varies; mini-mill electric steelmakers with limited secondary operations typically is without, while high-quality electric steelmakers and integrated plants uses the deslagging operation between one or several process steps.
The ladle deslagging is a critical step when the processing shifts between oxidizing and reducing (or vice versa). Any amount of slag carry-over in this transition will change the thermodynamics of the sub-sequent step. In addition, elements removed in previous refining steps present in the slag phase will revert back into the metal phase as conditions change.
Metal losses during deslagging is also of concern in steelmaking. This is of special focus during deslagging of iron prior to converter charging where iron losses potentially may be substantial[2], Figure 1.

Ferro-alloy production and deslagging
Depending on the type of ferro-alloy produced and the process at hand the deslagging operation has different objective:
In the most basic case no post-taphole operations take place and the slag is removed only to avoid slag entrapment in the final product. In this case focus is set on to avoid metal losses during the deslagging operation.
In other operations extensive post-tap hole refining takes place and conditions are similar to steelmaking; slag from previous steps should not enter the following step due to change of thermodynamic conditions. In addition, metal yield must be under control considering the high value of the ferro-alloy product.
The discussions following below will not elaborate any further on the ferro-alloy production but focuses on the impact of slag carry-over in steelmaking secondary operations

Effect of uncontrolled slag carry-over in steelmaking operations

Typical amount of slag carry-over
A previous study[1] performed in steelmaking operations showed that the amount of slag carry-over varied considerably. Typically, the amount of slag carry-over was 1.2 kg per ton but ranged between 0.7 and 2.3 kg per ton.
Although the amount of slag carry-over should always be minimized to obtain best conditions in the subsequent processing steps, some carry-over could be compensated for which requires that the amount is known. Variations of several hundred percent will be difficult to handle and cause process instability.

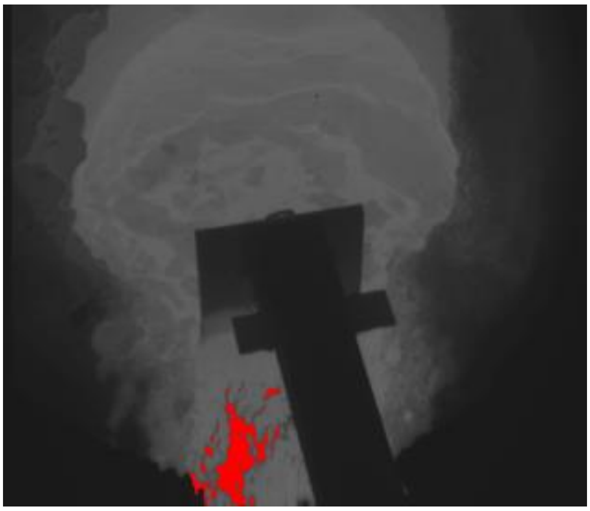

Figure 1: Metal losses (marked by red) during ladle deslagging as interpreted by vision analysis.

Effect on slag composition

Slag compositions in steelmaking targets different processing objectives and are tailored to the task. Thus, slag formers of known composition and amounts are added in order to meet the aim slag chemistry. If an unknown and varying amount of slag is transferred between operations the expected slag chemistry may not be reached and there is an obvious risk that refining objectives will not be met.

Considering the above mentioned slag carry-over amounts it should be noted that 2 kg per ton corresponds to an additional slag weight of about 10% in typical ladle operations where 15-20 kg synthetic slag per ton is added. The corresponding slag composition change is calculated in an example using a typical EAF and ladle slag, Figure 2.

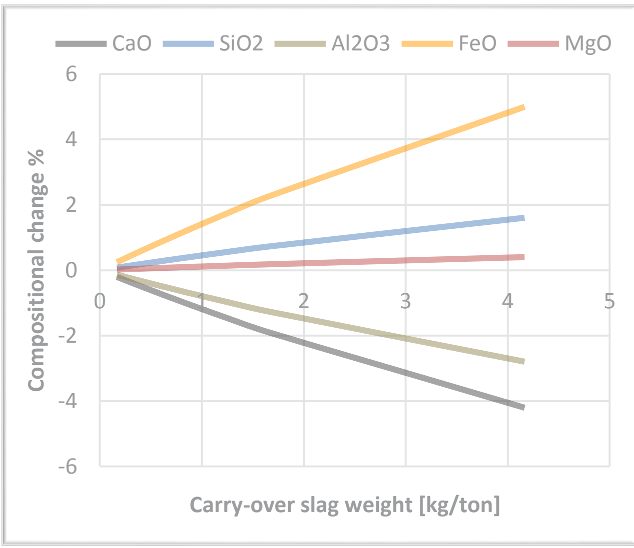

Figure 2: Relative compositional change of synthetic slag due to slag carry-over from electric arc furnace.

When studying figure 2 it is obvious that even a moderate amount of slag carry-over will make considerable contribution of undesired slag components such as FeO. These oxides will introduce oxygen into the system which will be reduced during the ladle operations, thus releasing undesirable oxygen into the steel melt.

Inefficient de-oxidation

In Figure 3 the effect of FeO content in the slag on the loss of aluminum in ladle and tundish can be seen from a previous study[3]. Not surprisingly, an increased level of FeO in the slag increases the aluminum loss.

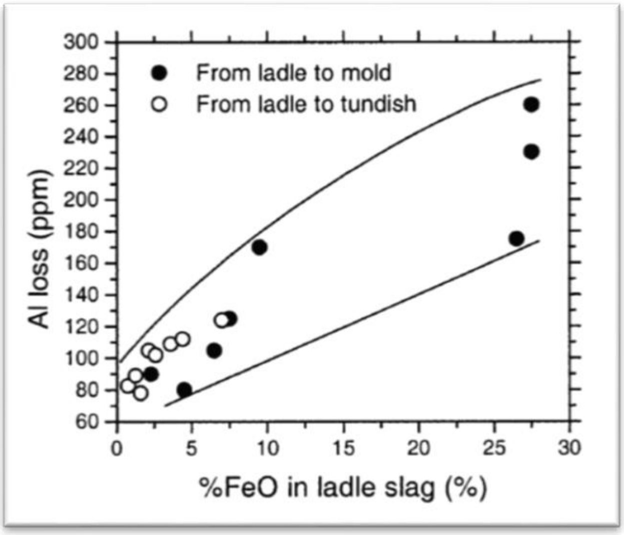

Figure 3: The loss of aluminum as a function of FeO-content in ladle slag[3].

Unknown FeO-content introduces uncertainty and uncontrolled variation in de-oxidation procedure. Consequently, the single most important process parameter in steelmaking – oxygen control – is then subject to unknown variations. Several operations will be affected, such as alloying and desulphurization, and one could expect an increased formation of non-metallic inclusions.

Yield losses in alloying

Alloying of elements with strong affinity to oxygen, e.g. Ti and Ca, will be affected by a variation in oxygen level. In addition, if the element is present at very low level it is even more sensitive since a considerable part of the total amount of alloy added would be oxidized when additional oxygen is present.

Formation of non-metallic inclusions

It is well known that there are variations in the steel cleanliness between heats, even when treatments apparently has followed the same procedure. This variation impacts negatively on the level and consistency of the quality of the steel products produced with focus on high cleanliness.

Typically, aluminum loss due to increased FeO and MnO content in the ladle slag forms Al_2O_3 which is then found as clusters in the final product if not removed during operations. This effect has been studied by Zhang and Thomas[3] who showed that the effect of the %FeO+%MnO content in the slag correlated to the amount of alumina inclusions found in the steel based on measurements in tundish, Figure 4. It is clear that even a relative moderate increase of the %FeO+%MnO concentration results in a considerable increase in the number of alumina inclusions.

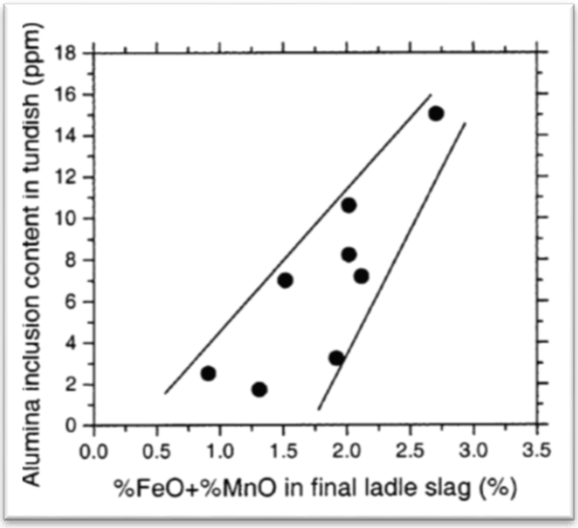

Figure 4: The effect of %FeO+%MnO content on the amount of alumina inclusions[3].

The effect on the desulphurization efficiency
It is generally known that the thermodynamic requirements on the desulphurization process require low oxygen potential and a high basicity slag. These are process parameters directly influenced by the amount of slag carry-over.

The slag Sulphide Capacity (C_S) is strongly dependent on the slag basicity in particular and the overall composition in general[4]. In practical steelmaking not only the Sulphide Capacity needs to be considered, but also other parameters that thermodynamically influences on the sulphur refining operations. The sulphur distribution ratio, L_S, is the best indicator of the sulphur removal efficiency in ladle operations. L_S usually defined as:

$$\log L_S = \frac{-935}{T} + 1.375 + \log C_S + \log f_S - \log a_O \qquad (1)$$

where L_S is the distribution ratio of $\%S_{Slag}$ and $\%S_{Steel}$, T the temperature, C_S the sulphide capacity, f_S the sulphur activity coefficient and a_O the oxygen activity.

Studying equation (1) it is clear that uncontrolled slag carry-over that increases the aluminum loss (oxidation) and causes Al_2O_3-formation will have a dual effect on the desulphurization thermodynamics:

i) a decreased CaO-content of the slag results in a decrease of C_S, and
ii) a decrease dissolved Al-content in the steel will increase the oxygen potential.

Both factors having a negative effect on the thermodynamics of desulphurization.

Calculations have been made using equation (1) with the assumption that i) FeO introduced by the slag carry-over will be reduced by Al to form Al_2O_3 in the slag, while keeping the mass balance intact between slag and metal, and ii) the oxygen activity in the steel was controlled by the Al-Al_2O_3 equilibrium at 1873K.

Figure 5 shows that the effect of slag carry-over is relatively strong; 2 kg/ton additional carry-over slag will lead to a decrease of the sulphur partition ratio by 30-40%.

The effect on processing stability
As discussed above the variation in slag carry-over influence on the processing thermodynamics. One should bear in mind that this variation also indirectly influences on the processing and production stability due to secondary effects:

i) Unexpected low alloying yield may require an additional, unplanned alloying step which may

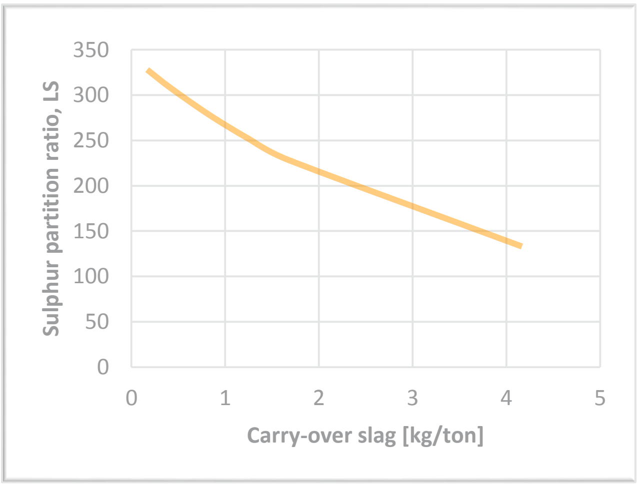

Figure 5: The effect of slag carry-over from electric arc furnace on the sulphur partition ratio.

lead to delays and violation of quality restrictions due to too late alloy addition.

i) Poor desulphurization may require an additional intermediate deslagging operation and/or additional lime additions which requires additional processing time.

LadleSlag™; a vision-based system for monitoring of ladle deslagging process

A vision technology system, LadleSlag, has been developed in order to increase the ladle deslagging operation repeatability, standardize handling, and register results. LadleSlag will assist the operator during the deslagging and enable future evaluation of operational results.

System overview

Infrared and near-infrared imaging is combined in order to quantify the surface area covered by metal and slag in a ladle. The video streams are analyzed to quantify the deslagging in real-time and present feedback to operators. By setting desired deslagging rate it is possible to standardize operation and avoid excessive slag carry-over.

System set-up

LadleSlag uses a combination of FLIR A-series infrared camera and a Basler Ace-series near-infrared camera as sensors. Images from the two cameras are captures in-synch and the image stream is fed to a computer dedicated to image analysis which is performed continuously. The analysis output and live image feed is displayed to the operator on a computer screen. Complimentary operator feedback is performed using a traffic light.

Analysis Overview

LadleSlag continuously analyses the image streams from the two cameras and starts/stops without operator action needed, Figure 6. Once a ladle is detected in the camera field of view the system tracks the movements and once the ladle is confirmed to be in the deslagging position the analysis starts to detect the slag-metal boundaries.

The analysis algorithm filters combine the inputs from the two sources with visual characteristics for slag and metal in order to identify the different phases.

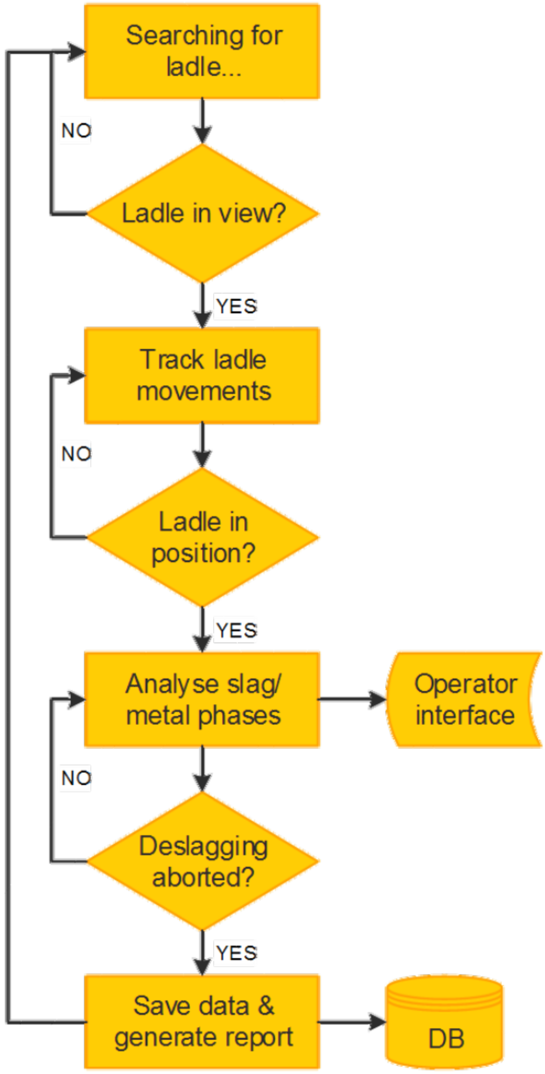

Figure 6: Basic principle of LadleSlag analysis.

Figure 7: Example of video frames showing the near infrared image (left), infrared image (center) and analyzed output (right). The analysis output codes thick slag as red, thick liquid slag as orange, thin slag as yellow and free metal surface as green.

Figure 7 shows an example of the image data input and the analysis output. The NIR and IR raw data images are shown to left and center, respectively. The image to the right shows the analysis where the metal (green), solid slag (red), thick liquid slag (orange) and thin liquid slag (yellow) are displayed. A deslagging rate is then calculated by using these fractions as input.
When the operator stops the deslagging the analysis detects the end and the system goes into the mode of searching for a new ladle.

System data handling
The LadleSlag saves selected images and data generated during the analysis. These data are saved in a local database and used to generate a heat report which contains start, intermediate and end images of the deslagging along with end result (deslagging rate).
Selected data are also subject to data exchange with plant systems for use in plant heat reports and/or data warehouse storage.

Operational experiences

The LadleSlag system cameras are positioned so that the deslagging process area can be covered at all times, thus, fully automatic registers all events taking place at the deslagging station.
The new processing information obtained when using the LadleSlag system has shown useful in several areas, some of which will be discussed below.

Operator handling
When studying the records from deslagging of numerous heats it was clear that the operator handling spread between individuals was too large due to no common definition of processing.
By using the LadleSlag as a training and follow-up tool a more uniform deslagging operation was achieved with a common understanding among the operators. Thus, process variations did decrease.

Production stability
Less process variations, as discussed in the previous sections, have been reflected in the production outcome after introduction of the LadleSlag system. A more uniform deslagging operation resulted in more stable subsequent processing with less variations in alloying yield and refining efficiency.
In addition, dedicated system settings for selected process routes have ensured that handling is balanced with respect to the sensitivity to slag carry-over in different processing cases

Product quality
Less production variation is reflected in a more uniform product quality. More uniformity will in practice result in higher product quality since this by definition must be determined by the least favorable outcome.

Safety and health
Camera systems for deslagging monitoring has opened for the possibility to introduce remote controlling of the deslagging operation. Thus, operators will have less exposure to dust and heat, and the residence time in high-risk areas is reduced.

Conclusions

A new system, LadleSlag, has been introduced that performs real-time monitoring of the deslagging process in order to control the amount of slag carry-over and allow follow-up on the deslagging operation performance.
Experiences from using the system shows potential advantages with respect to process stability, product quality, operator handling and safety.

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