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Analysis of splashing in Basic Oxygen Furnace through systematic modelling

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Abstract: This paper presents the results of using a systematic approach for identifying the interactions between splashing and the variables measured from the basic oxygen furnace. Splashing is a phenomenon in BOF, where a small portion of material (both slag and steel) is splashing from the BOF in an uncontrolled manner. This causes unwanted material losses, which requires additional processing phases resulting to the loss of time and money. Splashing is an undesired phenomenon and thus its analysis is important. Earlier the analysis is carried out mainly manually while the systematic approach used in this paper uses forward-selection for selecting the significant variables and multivariable linear regression as a modelling technique for identifying a model between splashing and process variables. The results show that the procedures used are able to find a variable subset that can be used for explaining changes in splashing. Despite the promising results the process and the studied approach needs more research in the future. Especially, the procedure used needs to be complemented with data selection.

Keywords: steel making, basic oxygen furnace, splashing, automatic variable selection

1. INTRODUCTION

Basic oxygen furnace (BOF) is a sub-process in steelmaking where hot metal is converted into molten steel by reducing the carbon content. To burn carbon, pure oxygen is blown from above while the batch is stirred using nitrogen and an inert argon gas blown from the bottom of the BOF. Controlling of the process is challenging because different additional materials are fed to the BOF during processing. These additions lead to unstable burning, for example, the addition of silicon causes disturbances. The consequence of unstable burning is material losses due to splashing. Splashing can be monitored by using image-based measurement.

The analysis of the causes of splashing is significant to identify and to avoid processing conditions leading to splashing. This analysis is earlier carried out mainly manually by clustering (Ruuska *et al.* 2006, Ruuska 2012). Some clustering criteria applied are converter type, heat size, target carbon content and amount of silicon added in the early stages of the process. The results obtained are promising but even better results may be obtained if automated procedures are used. Such an automatic procedure may be, for example, an algorithm which detects the significant process variables by identifying a model between splashing and process variables. This paper presents some preliminary results obtained from a study where models are identified between process variables and splashing.

The accuracy of the model obviously depends on the model structure and thus on the input variables. Thus the careful selection of input variables is very significant. It has been reported that excess variables lead to, for example, deterioration of model performance (Alexandridis *et al.* 2005), increased time consumption in model training (Guyon and Elisseeff 2003) and more difficult interpretation of the developed model (Smit *et al.* 2008).

In the literature, many methods have been proposed for selecting the appropriate variable subset. These methods can be roughly divided into filters and wrappers (Kohavi and John 1997). Filters are computationally efficient methods where variables are added to the model according to a ranking. However, the modelling technique applied also has an influence on variable selection. Wrapper methods take this into account and include the model identification procedure into the selection procedure. Typical wrapper methods are, for example, forward-selection, backward-elimination and genetic algorithms.

In this study, an automatic procedure is used for analysis of splashing. The results given are, however, preliminary. The algorithm uses a simple deterministic variable selection and multivariable linear regression models to map the interactions between splashing and process measurements. Instead of finding variables that individually explain splashing the aim is to find a subset of process variables able to predict splashing accurately.

2. MATERIALS AND METHODS

2.1 Basics of BOF

The idea of basic oxygen furnace in its simplest form (Fig. 1) is performed in a BOF with a basic refractory lining and an off-gas cleaning system. The BOF is tilted in order to charge the predetermined and weighed amounts of liquid hot metal and solid recycled steel. Gaseous oxygen is blown onto the metal bath until the estimated chemical composition and temperature are achieved. Fluxes such as burned lime and dolomite are added from the top of the BOF to regulate the

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process while for example iron ore is added as a coolant and ferrosilicon is added to produce additional heat. In normal cases, steel samples are taken and steel bath temperatures are measured from the tilted converter only after the end of the heat. At the end of BOF processing, the BOF is tilted to the other side and steel is tapped through a tap hole into a steel ladle. Slag is then tapped into a slag pot and the converter is ready for the next batch.

Specific aims for BOF include precisely described end point values for steel weight, temperature and composition. Carbon, phosphorus and sulphur and often also nitrogen, manganese and hydrogen concentrations need to be within the target windows. Typical end point temperatures rose are 1650 - 1700 °C or even higher depending on the steel grade and the subsequent process stages. Strict quality demands nowadays result that sulphur limits have to be lowered to prevent for example crack formation. Modern steel quality also required good phosphorus removal and the oxygen content in the liquid steel has become far more critical. Moreover, it became more critical to get the heat ready at the right time for the following process phases. (Boom 2003)

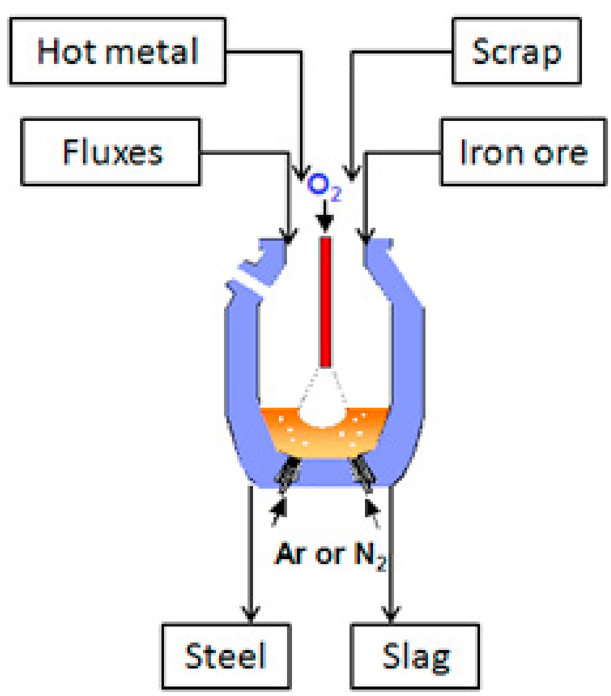

Fig. 1. Basic Oxygen Furnace.

2.2 Splashing

Splashing is a serious problem in BOFs. It causes economic losses and has therefore been widely researched. The negative effects of splashing are well-known, for example lower yield, different kinds of skull formation; in the lance, upper BOF cone, BOF mouth and gas hood; hard blowing, poor dephosphorisation and desulphurisation (Bock *et al.* 2000). To prevent splashing, the factors that cause foaming need to be known. A significant amount of research has been carried out on this field. Jung and Fruehan (2000) investigated the effects of FeO content, basicity, TiO_2, MgO and temperature of slag on foaming. Koch *et al.* (1993) determined the critical amount of blown gas when splashing starts, depending on the jet impulse, depth of crater and surface tension. Tang *et al.* (2008) studied the effects of lance height and bottom stirring flow rate on the mixing time, the amount of splashing, the penetration depth and level fluctuation using a water model. These studies found optimum levels for the parameters in the different phases of the heat. Luomala *et al.* (2002) investigated the effects of the following variables: lance height, gas flow rate, lance nozzle angle, bottom blowing, lance position and foamy slag. The reduction of the lance nozzle angle increased the total amount of splashing. The usage of bottom blowing increases splashing on the lower parts of the converter.

2.3 Measurements and Data Sets Used

The measurement data of different heats are obtained from the SSAB's Raahe Steel Works' database. An example of a heat is given in Fig. 2. The analysis of these heat trajectories in time-domain may reveal the interactions between process conditions and splashing. However, such an analysis is complex and significant interactions may not be found. The complexity arises from the great number of variables and their individual and combined effects on splashing. The dynamics of the effects of different variables also vary which makes the analysis even more complex. The time-dependency of the process is neglected in this study and the variables are averaged. The models are systematically identified for the averaged values from the whole data set and from the data sets corresponding to different phases of the heat shown in Fig. 2.

In this study, the first 20% of the data represents the ignition phase and the last 10% the end of heat phase. The remaining 70% represents the actual heat phase. Splashing occurs mainly in the set of actual blowing phase as shown in Table 1 which shows the average splashing in each data set. In later studies this splitting may need to be revised. An individual splashing value represents the numerical value which is calculated using the image analysis every two seconds and from these individual values the splashing integral is calculated. In Fig. 3 is shown two typical heats with different kind of splashing profiles (Ruuska *et al.* 2006).

Splashing measurement has been developed at SSAB's Raahe Steel Works. It is based on image analysis. At SSAB's Raahe steel works, there are video cameras for monitoring purposes under the BOFs. These existing cameras were utilised when the splashing measurement was developed. The picture pixels were analysed from a snapshot captured with the camera. The amount of splashing was investigated inside a predefined area by counting the ratio of bright and dark pixels; the limiting value of brightness was predefined. The ratio of bright and dark pixels gives a numerical value for the splashing. The splashing integral for the whole heat was calculated from the momentary values. The variation of splashing within the heats can be seen from Fig. 4. (Ruuska 2012)

The data sets include the measurements of 8 continuous and 9 batch variables from 397 heats. Continuous measurements are gathered every two seconds, which is the sampling sequence in Uniformance –automation data base system. Batch variables