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IFAC-PapersOnLine 48-17 (2015) 177–182

Data-driven Multivariate Analysis of Basic Oxygen Furnace Used in Steel Industry

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Abstract: This paper presents early results of the development steps taken in order to build a static model of a basic oxygen furnace for SSAB Raahe steel plant. The model aims for being used as a part of a plant-wide control system. Model development includes pre-processing and actual modelling steps. The modelling step uses a pre-selected set of input variables and non-linear multivariate regression models. The results show that the models for Mn, P and S changes are able to capture the main interactions even though the variance around the main trend is high. The prediction of Fe changes, however, is not successful. This research indicates that grouping or clustering of data or usage of other modelling techniques may improve the results greatly.

Keywords: basic oxygen furnace, non-linear multivariate regression, data-driven modelling

1. INTRODUCTION

Iron and steel are important raw materials for human infrastructure. They are needed for example in buildings, cars, ships and different kinds of domestic appliances such as fridges, freezers and dishwashers. Due to several applications where steel is needed, it is important that the production is well-organized and developed. It means also that multidisciplinary research on this business area is needed. The iron and steel industry is global business and many multinational corporations are main players on this business segment. Steel is normally divided into two main groups: stainless and carbon steel. The research presented in this paper is about production of carbon steel.

This paper presents early results from the FIMECC SIMP (System Integrated Metal Production) project, which is a large development and research project funded by FIMECC, TEKES and companies. FIMECC is a company, which objective is to increase the added value of innovation activities and R&D investments through its activities one of which is to fund research. TEKES is a Finnish funding agency for technology and innovation. In SIMP project, the focus is to make the sustainable systems work in an industrial setting of world class production facilities in a system integrated and in real-time. In Show Case 3 of the project, one objective is to develop a plant wide operation control system for hot metal production. In this paper we focus on material flows of basic oxygen furnace (BOF) that is an important part of the whole production chain. The data is acquired from SSAB Europe's Raahe steel plant.

Models have a major role in controlling the BOF process. However, BOF is a very complex process and thus modelling of it is very challenging. In the literature, two main approaches for modelling exist. The first approach uses analytical models derived from the phenomena and the reactions occurring in the BOF while the other approach uses the data-driven techniques. Analytical models are developed for the different phenomena in the process which can be combined to describe the overall process. For example, Li *et al*. (2001) derived a mathematical model for off-gas formation in a top-blown converter. Their model was dynamic and based on mass and energy balances taking the mass transfer effects and reaction equilibria into account. Martin *et al*. (2005) carried out a study where they focused on the mass transfer between liquid metal and slag. They studied the different blow practices and evaluated the effect of gas flow rate. Milosevic *et al.* (2011) studied the penetration of the high pressure oxygen jets to liquid metal in a steel converter. Their model included a simplified reaction scheme and described the hydrodynamic flow pattern in the cavern caused by the high pressure oxygen jet. Mass and energy balances are essential when studying any process. BOF is a batch process and thus the input and output flows are removed from the balances. Thus the balances include only the kinetic terms describing mass transfer and reaction kinetic effects. Kinetic equations for C, Si, Mn, P and Fe are reported in (Martin *et al.* 2003). A more detailed process model for the whole BOF process is reported in (Wei *et al.* 2001). The model includes also an energy balance and the thermodynamic effects are taken into account.

Even though the BOF process can be described analytically, it is reported being too complex to be represented by a set of analytic equations (Han and Zhao 2011). At least some process data is needed to fit the models for the process under investigation (Jalkanen and Holappa 2014). Thus the data-driven techniques may be beneficial to use. Some examples of data-driven modelling of BOF can be found in the literature. Cox *et al.* (2002) and Frattini Fileti *et al.* (2006) used an artificial neural network (ANN) to evaluate a proper amount of blown oxygen and added coolant to reach the target end-

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2015.10.099

point values for temperature and carbon content. The same task was implemented with the ANFIS model in (Han and Zhao 2011).

The BOF process is challenging for the measurements due to hazardous environment. Thus the models can be used to gain significant information from the process indirectly. For example, the extension of the reactions can be evaluated based on the analyses taken from the off-gas (Jalkanen and Holappa 2014). Another example of the indirect measurements is a soft sensor reported in (Evestedt and Medvedev 2009) where acoustic sensor readings are used to evaluate and regulate the slopping phenomenon.

The models reported in the above mentioned references are dynamic. The analytical models generally are used for describing the phenomenon in the process while the data-driven models clearly aim for process control. In this study, a static model of BOF for SSAB Raahe steel plant is built to be used in a plant-wide process control system. A data-driven approach is used where a non-linear multivariate regression (MLR) model with quadratic and two-variable interaction terms is identified to predict the change in the amounts of Fe, Mn, P and S in BOF. The input variables for the models are pre-selected from a set of variables. The modelling work includes data pre-processing and analysis together with the actual model identification.

2. MATERIALS AND METHODS

2.1 Process description

Carbon steel production can be divided into ore-based and recycled steel based schemes. In this case, production is carried out through the blast furnace route. The raw materials charged into a blast furnace are iron ore in pellets and coal which is produced in coke ovens. Heated gas and some additives are used to bring additional energy into the process. In the blast furnace process, the iron oxides within iron ore are reduced into metallic iron using carbon and carbon monoxide (Eq. 1). The objectives of blast furnace are to produce hot metal that meets the process requirements and is at a correct temperature. Blast furnace process is followed by an oxygen steelmaking step.

$$FeO_3 + 3\,CO \rightarrow 2\,Fe + 3\,CO_2. \qquad (1)$$

The BOF process uses a steel converter vessel which is tilted to charge the predetermined amounts of liquid hot metal and recycled steel. Oxygen is blown onto the metal bath to reach target composition and temperature. Additives such as burned lime and ferrosilicon are added during blowing to regulate the process. Many chemical reactions occur during processing. These reactions are not listed here but can be found in (Brooks and Coley 2002). The vessel is tilted again after the blow has ended and steel is tapped through a tap hole into a steel ladle. Slag is tapped into a slag pot. The aim of the BOF is to reach the temperature and composition targets. For example carbon, phosphorous and sulphur and also nitrogen, manganese and hydrogen concentrations need to be within the specified limits. (Boom 2003) A more detailed description of the BOF process can be found, for example, in (Ruuska 2012) and (Jalkanen and Holappa 2014). In this study, the amounts of chemical elements in the discharged steel are predicted based on the processing conditions and BOF feed.

After the basic oxygen furnace the needed additives to meet steel specifications are charged into a vessel and then a batch is discharged from the BOF to a ladle. There are three possible process routes for the ladle depending on the steel quality. In the CAS-OB process, the alloy additions can be made under an inert argon environment. It allows simultaneous addition of Al and O_2 gas blown through a top lance. These react to form Al_2O_3 and generate a considerable amount of heat due to exothermic nature of the reaction. The CAS-OB process therefore results in chemical heating of the liquid steel. A ladle furnace's (LD) primary functions are reheating of liquid steel through electric power conducted by graphite electrodes, homogenisation of steel temperature and chemistry through inert gas stirring, formation of a slag layer that protects refractory from arc damage, concentration and transfer of heat to the liquid steel, trap inclusions and metal oxides and provide the means for desulphurization. A vacuum tank degasser (VD) is used to reduce the concentrations of dissolved gases (H_2, N_2, O_2) in the liquid steel, homogenise the liquid steel composition and steel temperature, remove oxide inclusion materials from the liquid steel and provide the means and technical conditions that are favourable for the final desulphurisation. In continuous casting steel is casted into slabs. The final processing stages in Raahe steel plant are the rolling plants for the plates and the strips. Rolling is a metal forming process in which metal slab is passed through one or more pairs of rolls to reduce the thickness and to make the thickness uniform.

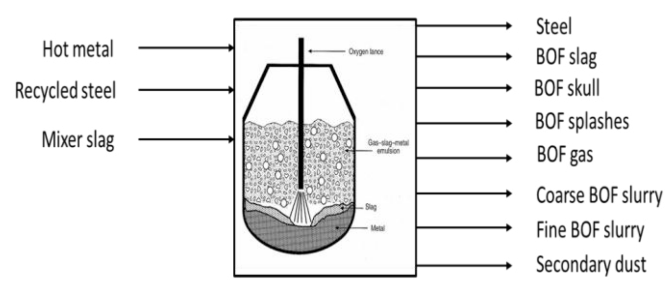

Fig. 1. Inputs and outputs of BOF.

2.2 Data sets

The original data sets are collected from the Raahe steel plant databases. Partly they are acquired from different automation systems, so for example synchronizing is an important issue. Data includes information from different sources and in different formats. The batch-wise information available includes chemical compositions and the amounts of the hot metal fed into the process and steel discharged from the process. Also the amount of recycled steel loaded into the process is measured and collected in the data sets. Recycled steel is further divided into eleven different types. The processing conditions such as temperature, initial and final lance heights, hot metal surface level, bottom stirring and amounts of additives are also acquired. The data sets collected also include information that is not obtained from every batch. Such information is for example laboratory analyses of certain additives and slag and the chemical composition of recycled