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Estimation of FeO content in the steel slag using infrared imaging and artificial neural network

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ABSTRACT

The paper presents the novel method of fast and contactless estimation of iron oxide (FeO) concentration in steel slag during discharge process in steelworks. The infrared imaging and artificial neural network are the key tools used in the research. The imaging system consists of three cameras that work in the different wavelength ranges. The novel idea based on steel and slag radiation parameters extracted from the sequences of images is described. Radiation data that are the most correlated with FeO content in steelmaking slag are selected and use as input variables for ensemble of Artificial Neural Networks (ANN). Different parameters and configuration of the ANN were tested to define the most effective ones. The final result of FeO content estimation is presented and validated with the values obtained from the chemical analysis.

1. Introduction

Today thermovision is widely used in industry, mainly as a qualitative research imaging method. One of its area of applications is metallurgy. Infrared cameras are used in steel works during the discharge process, where a steel flows out from a converter to a ladle [1–4]. After the steel, the oxidising slag appears. This is a by-product of steel production, so the discharge process has to be interrupted as soon as the slag starts flowing out of the converter. One of the method to detect slag in the stream of steel and stop the discharge is the thermovision. It takes advantage of the differences in thermal radiation of steel and slag, due to the emissivity disparity [1–4]. This allows to detect the slag using infrared imaging despite it has almost the same temperature as the steel.

The slag parameters have the major influence on the later technological process of steelmaking. The FeO content in the slag is one of the particular importance as it affects on over-oxidation and quality. In general the knowledge of the FeO concentration in the slag right after the discharge process makes possible to adjust further technological process in order to achieve target parameters of the steel. Nowadays, in most methods of FeO content estimation, a probe must be inserted into the ladle to take a sample of the slag and analyze it. Moreover, the high accuracy is achieved only by time consuming laboratory analysis.

The authors proposed to use the radiation measurements not only for stopping the discharge process but also for quantitative measurements of slags parameters, mainly FeO concentration. However, there are two main problems with the measurement of radiation levels in steelworks. Firstly, there are changes in atmosphere transmission around the ladle, which leads to the strong and time-dependent damping of radiation intensity in various spectral ranges. Secondly, the stream during discharge is not uniform and not stable, with skulls dropping from the edges.

Consequently, the multi-camera system was designed and multivariate statistical analysis using the radiation parameters of the steel and slag in various spectral ranges is proposed. The artificial neural network was used as a regression tool. It estimates FeO content based on the calculated radiation parameters. The designed system allows contactless measurement, without the necessity of delivery a sample to the laboratory. Moreover, the estimation results could be obtained instantly, right after the end of discharge, which is vital information in further steelmaking process. The efficiency of the developed technique has been verified using the results of the chemical analysis.

2. Estimation of FeO content in the slag

Metallurgical slag is a multi-component compound, mainly of oxides, which plays a crucial role in metallurgical processes. In liquid state, slag is regarded as an ionic liquid, however in practice, usually

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slags are approached in line with molecular theory as multi-component solutions, which is sufficient for utilitarian description of metallurgical processes [5].

Substantially, slag is a by-product of crude iron and steel manufacturing. In the steelmaking process it absorbs chemical compounds formed as a result of refining (additives oxidation), desulphurization, dephosphorization and deoxidation of steel as well as wear of refractory lining, and a result of absorption of impurities introduced along with charge material [5].

Steelmaking slag, of much lower density than iron, reaching from 3200 to 3600 kg/m^3, depending on the composition, floats on the surface of steel, thus forming a layer with chemical impact on the metal and isolating it from atmospheric air. Depending on the volume of slag, and degree of foaming thereof, the layer is from several to several dozen centimetres thick; in extreme cases, e.g. in oxygen converter during refining – the thickness may be much higher.

The slag, absorbing products of metallurgical reactions, alters its chemical composition during the process. However, chemical composition of the slag is not a simple resultant of accumulation of the products of steel melting and impurities introduced along with charge material, which as a result of metallurgical processes are not present in the metal. Chemical composition, and thus properties of slag, is intentionally formed by proper selection of additives defined as slag-forming materials [6].

Presence of particular components in slag and mutual proportions between them decide on slag's interaction with steel, and as a corollary on the properties of steel. At particular stages of steel production, various goals are realized, and thus various interaction of slag and steel is necessary.

The most significant oxides composing steelmaking slag are CaO, SiO_2, MgO, Al_2O_3, FeO, MnO, P_2O_5, Fe_2O_3, and among others Cr_2O_3, TiO_2, Na_2O, K_2O and other are also important: CaF_2, CaS, CaC_2 are to be deemed the most important non-oxide compounds [6].

FeO concentration in slag in steelmaking processes is of very significant meaning, and thus knowledge of the said parameter facilitates application of adequate technological procedures and improves production process. Value of the said parameter is intentionally altered during steel melting as at various stages of production, various goals are pursued, which requires various interaction of slag and steel.

For example, presence of FeO in slag facilitates dephosphorization of steel [5,6]. Due to that, steel is usually subjected to dephosphorization during refining, as at that time slag is rich in iron oxide. Moreover, FeO facilitates solution of lime in slag, and thus accelerates slagforming processes and achievement of higher basicity. The desired content of FeO in converter slag is at least a dozen or so, and frequently much percent.

Completely different requirements concerning slag are valid during ladle treatment. At this stage of production, one aims at elimination of FeO from slag. Usually it is assumed that slag during ladle treatment should not contain more than 1.5% - 2% FeO + MnO, (in ladle treatment FeO is usually balanced with MnO), and sometimes requirements are even more stringent. The desired low content of these oxides in slag stems from the conditions required in steel deoxidation and desulphurization, which occur during ladle treatment.

Converter tapping of steel constitutes a frontier between two various processes, and thus different ways of steel refining. Cutting-off converter slag, and in case when the said operation is not fully successful, estimation of the volume of FeO that got into the ladle, is of fundamental meaning for ladle treatment. Knowledge of FeO volume which got to casting ladle allows to optimize slag deoxidation, and as a corollary the use of deoxidants, thus impacts production cost and metallurgical purity of cast steel.

There are different methods that may be applied for determination of FeO content in the steel slag. In case of scientific research related to the metallurgical processes, it is necessary to know the slag's chemical composition. Commonly it is required to have high accuracy of this analysis while its duration time is less important. Hence classic analytical chemistry approaches are still in use, e.g. the titration process [7,8]. The measurement of Fe^{2+} content in the slag is performed e.g. with the potassium dichromate titration [7]. For on-going process control it is enough to know the most important parameters, however faster analytical techniques are necessary, e.g. X-ray Fluorescence Spectrometry [9], Laser-Induced Breakdown Spectrometry [10] or others [11]. Nonetheless, those methods require to get and prepare the sample, and it takes time. Sometimes it lasts too long, despite the efforts to shorten the sample preparation time [10]. Therefore there are methods for estimation of FeO and MnO content in the metallurgical slag by measuring its oxidation potential [12,13]. It may be done with immersion sensors, such as “Celox SLAC” manufactured by Heraeus Electro-Nite. Due to the importance of the FeO content in the slag, there are also electrochemical FeO sensors developed [14,15]. It guarantees fast enough measurement for on-going process control, but it is not contactless and generates additional costs related to its application.

The estimation of the FeO content by the system based on artificial neural network was also developed [16]. The input data for ANN were 35 technological variables of metallurgical process e.g. iron are or coke mass and their precise composition. Moreover, the main aim of that project was to control the silica and sulfur concentration in the hot metal [16].

However, estimation of FeO concentration in the converter slag, based on balance calculations is difficult, as the said oxide is a product of oxidation of the main component of charge material, i.e. iron and atmospheric oxygen [17].

Meaning of FeO in metallurgical process and difficulty in estimation in the real time constituted a motivation to start up works aimed at development of contactless and immediate method of estimation of FeO content in the converter slag during tapping. FeO concentration estimated in such manner may be a parameter used in on-going optimization of steelmaking.

3. The proposed method

3.1. Infrared based multispectral imaging system

The first stage of the research involved elaboration of measuring position configuration, which took into account the specific conditions of the steelworks chosen for measurements. During selection of the optimal system placement many conditions were taken into account, e.g. safe distance from oxygen converter and uninterrupted view of the whole process of material discharge to the ladle. Considering all technical aspects, it was decided to localize the system at the platform of after furnace processing. The system with the cameras were placed opposite the converter, at the level that provide direct view of the discharge stream from the converter to the ladle, as shown in Fig. 1.

The radiometric system for estimation of FeO content in the steel slag includes three cameras:

- Uncooled, long-wavelength thermal camera FLIR® SC660 sensitive to the spectral infrared range $\Delta\lambda_1$ (7.5–13 μm, LWIR *Long-Wavelength InfraRed*),
- Cooled, mid-wavelength thermal camera CEDIP® Titanium sensitive to the spectral infrared range $\Delta\lambda_2$ (3–5 μm, MWIR *Medium-Wavelength InfraRed*). In case of our research it was necessary to use an additional filter due to very high temperature of observed steel and slag. This narrow band-pass filter with center wavelength λ_c = 4 μm was to prevent the saturation of the camera detector.
- Digital Single Lens Reflex (DSLR) camera Nikon® D5100 with Nikkor 55–300 mm lens, sensitive to the spectral range of visible light $\Delta\lambda_3$ (380–740 nm). In fact, the CMOS matrix in this camera contains separate red, green and blue filters formed in the Bayer array. Thanks to this fact, it was possible to acquire three independent images, separately for each color component.