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Research article

How coke optical texture became a relevant tool for understanding coal blending and coke quality

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ABSTRACT

The scope of this work was to examine the cause-effect relationships between the characteristics of coking coals and blends, and the optical texture and the quality parameters of the resultant cokes. Although a detailed quantitative analysis of the several anisotropic carbon forms, according to size and shape, was carried out, the data used for the calculation of optical texture index (OTI) were compiled into only five microtextural categories: isotropic, incipient anisotropy, circular or mosaics, lenticular and ribbon. Considering the optical texture components of the carbon matrix of the cokes obtained from individual coals, a simple mathematical model is presented on the basis of the additivity law in order to estimate each optical texture component within the matrix of the cokes produced from coal blends. When looking at the good linear relationship between experimental and calculated data, it can be concluded that the proposed model is a useful way of describing the optical texture of cokes from coking blends. As an additional top objective of this study, the coal blends were made for the purpose of lowering the amount of high-cost coking coals. The individual coals and their blends were carbonized in a pilot scale coke oven and, then, the resultant cokes were evaluated in terms of mechanical strength before and after partial gasification with CO_2. The degree of coke anisotropy clearly increased with the coal rank and it is correlated to coke reactivity and strength after reaction. From coke characteristics, the optimum quantity of each low-cost coal in the blends to avoid a deterioration of coke properties and structure was established.

1. Introduction

The relatively high price of prime coking coals and their scarcity worldwide have lead coking companies to look for alternative raw materials to redesign blends with coals that have lower prices, but, at the same time, lower quality. In this context, the main goal of coking companies is the incorporation of low-cost coals into blends while maintaining coke quality. Nowadays most ironmaking companies characterize coke quality by three parameters, so called technological parameters, which basically consist of measuring coke mechanical resistance to size degradation (usually based on a rotating drum test performed at room temperature), reactivity towards CO_2 (Coke Reactivity Index -CRI-) and mechanical resistance to size degradation after coke particles have undergone reaction with CO_2 (Coke Strength after Reaction -CSR-). These standardized tests were developed aiming to estimate coke degradation throughout its consumption in a blast furnace, where coke has to fulfil three important roles: i) a thermal role, to provide heat for the endothermic requirements of chemical reactions and the melting of slag and metal; ii) a chemical role, to provide a reducing agent at the middle part of the blast furnace by means of its reaction with CO_2 in order to produce the necessary carbon monoxide for the reduction of the iron oxides, and also to provide a carbon source for both direct reduction and iron carburization; iii) a physical role, in which coke provides a support bed for the iron-bearing burden and acts as a permeable bed, necessary for slag and metal to pass down and gases to pass up.

Due to the complexity of coal blends used worldwide, coke quality prediction has been a major issue for many years. Therefore, much effort has been made over the years to find correlations between coal properties and technological parameters of coke and so predict its quality. It is well known that coke reactivity and mechanical resistance are associated with coal properties, i.e. petrographic parameters such as coal rank [1–6], maceral composition [3–7] and composition of mineral matter [7–10]. However, a recent review [4] concludes that there is still no universally applicable prediction model due to the great diversity of the coals used for cokemaking.

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To gain insight into coke reactivity and post-strength, the organization of carbon structure is very important. During coal carbonization molecular oriented domains are formed [11]. The size of these domains can vary from nano to micro scale and it is related with coke quality, especially coke reactivity to CO_2. Technics such as transmission electron microscopy, X-ray diffraction and Raman spectroscopy [12,13] has been used to characterize the nano scale organization of carbon in cokes. Optical microscopy is another technic that is widely used to characterize the nature of the carbon in coke, development of its crystalline structure and the degree of optical anisotropy [2,14–22]. The micro scale domains that is characterize by optical microscopy is called coke texture. The interest on coke optical texture is fundamentally based on its well proved relationship with coal properties [2,14–24] and also coke technological parameters [18–29]. Moreover, the optical texture of coke can provide important information about coking conditions, enabling the detection of frequent operational problems in the cokemaking industry [18]. Additionally, the optical texture of coke provides a way of understanding how maceral components act during the coking process [25,30,31] and the impacts of coal weathering [32] and different additives such as inert [33–35] and binder materials [36–39] on coke quality. In summary, the optical microscopy of cokes can be regarded as an old technique which has already proved its strength for better understanding the formation mechanism of the carbon matrix of metallurgical coke, the variations in the anisotropic development of coking coals during carbonization and, in turn, the coke-forming ability of the parent coals, the interactions between coal blend components and between coal and additives. Thus, the optically anisotropic components of coke matrix may be also relevant in coal blending and coke quality in the industrial situation.

One of the most recognized classification systems for coke microtexture description was proposed by U.S. Steel in the late 1950s, through the studies of Schapiro and Gray [17]. The measurement criteria and coke texture descriptions used in this system were developed from microscopic observations of semicokes and cokes produced from coals covering a wide range of ranks and later became a standardized procedure. Nevertheless different laboratories used adapted or simplified terminologies as shown by Coin [19] and Singh et al. [40], and the applicability of this knowledge to everyday cokemaking practice still is a challenge. The incorporation of complex classification systems into prediction models is not easy and there are many different approaches to transform the information derived from coke classification into a single figure which could reflect the differences in coke optical texture. Much research has proposed to evaluate the degree of coke anisotropy by a single number [16,26,41–47], which is usually reported as coke anisotropy index or optical texture index (OTI). Generally, this is done by associating numerical factors to each textural component in the coke matrix, including or not the organic inert and then multiplying these factors by the proportions of each of the optical textures found by point-count analysis. Recently methods based on coke anisotropy using automated optical microscopy have been also proposed to describe and simplify the usage of coke optical texture [40,46].

According to the strength already proved by the coke petrography and the substantial contributions to coal carbonization, it is expected that this technique will continue to expand our knowledge of cokemaking and that new applications will emerge. However, some improvements are still required to solve some of the challenging problems such as a detailed automatic quantification of the different carbon components within cokes. The progress in optical components of the microscopes, microelectronics and computer technology which nowadays is achieved as well as new techniques in the coke petrographic analysis [40,46,47], the evaluation of coke optical texture components would become a faster, simpler and more flexible technique.

In this work, the primary objective is to establish the relationship between the optical texture of the individual cokes and those produced from the blends and to relate it to the coal blend composition and the coke quality parameters. Afterwards, it provides the development and application of a simple mathematical model to predict the microtexture of the cokes produced at a pilot scale. This task was proposed as an additional objective of a clear technological character which was addressed to maximize the amount of target coals (low-cost coals) in a coal blend, as they could be included in a real industrial scenario.

2. Experimental

2.1. Coal characterization

Five coking coals (H, M1, M2, M3 and L) of different rank, rheological properties and geographical origin were selected for the preparation of coking blends for metallurgical coke production at a pilot scale. The selected coals, commonly used by cokemaking industries and available to the international coal market, were provided by a Brazilian steelmaking company. The coals were characterized in terms of proximate analysis (ISO562 and ISO1171 standard procedures for volatile matter and ash content, respectively), total sulphur (using a LECO S-144DR), Gieseler plastometry (ASTM D2639), expansion/contraction (ASTM D2014) and petrographic analysis (ISO7404/5). Ash chemical composition was determined by using X-Ray fluorescence (Siemens-Bruker SRS3000) according to ASTM D4326 standard procedure. The major elements analysed (Si, Al, Na, K, Ca, Mg, Fe) were used to define the basicity, catalytic or alkali index which is taken as an indicator of the catalytic or refractory activity of the inorganic components during the CO_2 gasification of coke and widely used in several prediction models of CRI and CSR reviewed by Diez et al. [4,6]. The basicity index is defined by the ratio between the basic and acidic oxides in the coal ashes (A) [48] and can be expressed as Eq. 1:

$$BI = A\left(\frac{Na_2O + K_2O + CaO + MgO + Fe_2O_3}{SiO_2 + Al_2O_3}\right) \quad (1)$$

The main characteristics of the five selected coals, which were classified as: high-volatile (H), medium-volatile (M1, M2 and M3) and low-volatile (L) bituminous coals, according to the ASTM D388 classification, are summarized in Table 1.

Ten different coking blends to be carbonized at a pilot scale were prepared and classified into three sets: M1-X, L-X and H-X, with X being the amount of a specific coal added, which depends on the base coal chosen for increasing its proportion in the blend (Table 2).

2.2. Pilot-scale carbonizations

Carbonization tests of the individual coals and blends were performed using a pilot-scale oven of 240 kg capacity under experimental conditions which was aimed at simulating the industrial practice of coking plants. The dimensions of the oven are: 930 mm H × 830 mm L × 450 mm W. The crushed coals and blends (approximately 80% at <3 mm) were charged by gravity in a pre-heated oven at 1100 °C, the coking time was set to 20 h and the temperature in the centre of the charge was 1010 ± 20 °C at the end of the process. The moisture content of the coal was adjusted to 8 wt% and the bulk density calculated on a dry coal basis was kept as close as possible to 810 ± 5 kg/m^3 in order to avoid any effect of this operational parameter on the coke quality. Under the conditions tested, coals can be classified as safe or dangerous feedstock for coking, according the maximum coking pressure developed during the process.

2.3. Coke characterization

Technological characteristics of cokes were evaluated by: (i) proximate analysis; (ii) cold mechanical strength in a JIS drum, according to the Japanese Industrial Standard -JIS- method (JIS K2151); and (iii) reactivity towards CO_2 (CRI) and the mechanical strength of the partially