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Full Length Article

Fractographic approach to metallurgical coke failure analysis. Part 3: Characterisation of fracture mechanisms in a blast furnace coke

Richard Roest [a,*], Hannah Lomas [a], Sushil Gupta [b], Riku Kanniala [c], Merrick R. Mahoney [a]

[a] Centre for Ironmaking Materials Research, School of Engineering, The Newcastle Institute for Energy and Resources, University of Newcastle, University Drive, Callaghan, NSW 2308, Australia
[b] School of Materials Science and Engineering, UNSW Australia, Sydney, NSW 2052, Australia
[c] SSAB Europe, Raahe, Finland

HIGHLIGHTS

- A fractographic approach identified blast furnace coke failure mechanisms.
- Breakage behaviour of cokes was influenced by porosity and interface properties.
- Breakage behaviour of blast furnace cokes was notably different to feed coke.

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ABSTRACT

Metallurgical coke samples across the tuyere level of an operating blast furnace were analysed using a fractographic approach to identify and quantify various coke failure mechanisms. Tuyere level cokes displayed different failure mechanisms compared to the feed coke, implying a strong influence of the blast furnace reaction environment on the modification of coke failure mechanisms. The conchoidal and brittle overload type failures were noted to have an effect on the propagation of transgranular and intergranular crack growth in the coke microstructure. Feed coke breakage behaviour was strongly influenced by existing fissures and conchoidal fracture, while the breakage of the deadman coke lumps was dominated by pore wall collapse through intergranular crack growth in combination with erosive wear.

The porosity at the IMDC–RMDC interface in coke has been identified as a critical parameter contributing to coke failure at tuyere regions. This fractographic study demonstrates that the fracture faces show evidence of the varying failure mechanisms presented in the preceding manuscripts (Part 1 and Part 2), in addition to the erosive wear resulting from the blast furnace exposure. However, further studies are required to establish the association between the identified coke failure mechanisms and coke texture, which has implications for improving coke performance in a blast furnace.

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1. Introduction

Metallurgical coke is essential to the production of iron from the ferrous burden (comprising iron ore, sinter, pellets, etc.) in the blast furnace [1]. In addition to acting as a reducing agent and source of thermal energy, metallurgical coke provides both mechanical support and a permeable matrix, thereby facilitating the extraction of the molten iron product and the percolation of gases [2]. For these latter roles, the precise nature and strength of the coke is critical.

By far the most demanding roles placed on coke in the blast furnace are to maintain the permeability of the furnace and to support the ferrous burden. Any process in the blast furnace that generates fine materials has the potential (depending on the location) to severely impede the permeability of the furnace. Hence understanding the breakage of coke in the blast furnace is of critical importance. To date, extensive research has been conducted to enhance understanding of the link between coke mineralogy and the chemical reactions it undergoes [3–8], as well as reactions that occur in the blast furnace that may modify coke structure, properties and its breakage characteristics [9]. What has been lacking is the determination of which breakage mechanisms dominate in the different locations of the blast furnace.

* Corresponding author.
E-mail address: Richard.Roest@newcastle.edu.au (R. Roest).

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The sampling of coke via the blast furnace tuyeres is a common method of obtaining coke samples from the different zones of operating blast furnaces to gain an enhanced understanding of the mechanisms by which the coke degrades in the furnace [1]. Dissection of non-operating furnaces has been used in the past [10,11] but is currently restricted by economic and huge logistic constraints.

Matched feed coke and coke collected from the bottom of an SSAB Europe (Raahe, Finland) medium sized blast furnace through a tuyere drilling were used for a preliminary study into the factors that influence coke degradation in different zones of the blast furnace. The aim of this paper is to apply the technique of fractography, which is used to understand the direct causal sources of mechanical failure in other material systems, such as ceramics and metals, to understand the breakage mechanisms of both the feed coke and the coke collected in the tuyere drilling.

Recently, we have successfully applied fractography to identify the breakage mechanisms and microstructural weaknesses in whole stabilised pilot oven metallurgical coke lumps from both single coals (Part 1) [12–14] and binary coal blends (Part 2) [13,14]. These studies identified that numerous factors can contribute to the failure of a particular coke. These depend on the properties of the original coals and the coking conditions. However, in the case of blends, it is not always easy to predict which features of the coke microstructure will be susceptible to high stress concentration and dictate the mechanism of coke breakage.

The effect of blast furnace conditions on the chemistry and physical properties of the tuyere-level cokes has previously been examined using coke collected from the tuyere drilling of SSAB Europe's blast furnaces [7,15,16]. In this study, we report on the response of similar tuyere-level cokes to mechanical stress and identify the weak points in the coke using our fractographic approach. The cokes studied were sampled from four different locations in the tuyere drilling (see Table 1). For simplification, these locations are referred to as 'bosh', 'raceway', 'bird's nest' and 'deadman' in this paper.

The fracture surface formed during fractographic testing was examined using the method described in Part 1 [12] to develop an understanding of where the fracture occurred and the mechanism by which it propagated. This allowed us to successfully build a picture of the microstructural features and regions of stress concentration in the coke as it descends into the tuyere-level. These features and fracture mechanisms were then compared with those of the corresponding feed coke, leading to identification of features in the feed coke that may affect the performance in the lower blast furnace. The breakage mechanisms were summarised for both the feed and tuyere level cokes using quantified radar graphs.

2. Experimental

2.1. Coke sample selection

Coke lumps from a tuyere-drilling campaign from an operating blast furnace (BF#2 located at SSAB Europe, Raahe, Finland) from four selected locations were used as a single trial for this study. Further details of tuyere drilling and blast furnace operations can be found in a previous ACARP project report [15]. Matched feed and tuyere coke samples were examined visually and via our fractographic testing protocols to determine coke strength and breakage behaviour as a function of the location in the tuyere probe. The feed coke and tuyere coke lumps from four different depths were examined. Size characteristics and depth of the coke collected from the tuyere probe are shown in Table 1. Lumps greater than 19 mm in size were analysed from each of four locations in the tuyere probe.

2.2. Fractographic analysis

Our fractographic approach consisted of breaking the coke lumps under a compressive load in a Shimadzu universal tester (Shimadzu Autograph AGS-10 kND), using a previously developed method for fracture of coke lumps of a similar size [12]. Compared to our previously published work [12], the coke lump size was quite small, so this alternative method for initiating fracture of the coke was developed. Experiments were carried out at a cross-head speed of 2 mm/min and maximum load set at 10 kN. Load versus displacement graphs were recorded, allowing determination of the maximum load required to induce failure.

A three-step approach was applied to analyse and quantify the modes of failure and microstructural weaknesses observed on coke fracture surfaces on three different magnification levels (macro, micro and submicron), using the method we reported in Part 1 [12]. For quantification, 8 stereo micrographs from 2 to 3 fractured coke lumps were analysed from each location in the tuyere probe.

A description of each feature and mechanism of failure that we have observed in metallurgical coke and quantified are given in Tables 3 and 4 of Part 1 [12]. The analysis technique produced a scaled output for each of the contributing factors (see Table 2). The overall mean for each coke and the standard deviation of the values between the analysed micrographs are shown in Table 3. Properties were assumed to follow a normal distribution. N.B. The standard deviation was not calculated for parameters for which there were insufficient measurements (for example external crack length). The compiled data was used to generate radar diagrams to summarise the contributing factors to the failure of both the feed and each tuyere level coke.

3. Results and discussion

3.1. General characteristics of the blast furnace coke studied

Before considering the differences in the fracture properties of the coke lumps with increasing distance in the tuyere probe, the properties of the feed coke should be examined. This is important not only to identify the inherent microstructural weaknesses in this coke before it is exposed to the harsh environment of the blast furnace, but also because the mechanisms of degradation that the coke will be susceptible to in the furnace are highly dependent on the properties of the feed coke [1], as well as the conditions under which the furnace is operating [1].

Table 1
Size distribution of coke lumps in various locations of the probe, representing four zones at tuyere level.

Coke	Distance in the tuyere probe (m)	Coke size distribution (wt%)						
		+19 mm	11.2–19 mm	8–11.2 mm	3–8 mm	2–3 mm	0.45–2 mm	<0.45 mm
Bosh	0.125	87	8	2	2	0	0	0
Raceway	0.625	70	10	5	12	1	1	1
Bird's nest	1.125	43	17	8	17	4	7	4
Deadman	1.875	38	20	10	18	3	7	3

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