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Influence of coke ash on blast furnace hearth behaviour

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INFLUENCE OF COKE ASH ON BLAST FURNACE HEARTH BEHAVIOUR

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ABSTRACT

Liquid iron in the ironmaking blast furnace picks up more than half of its carbon while percolating through the packed coke bed in the deadman and hearth of the blast furnace thus the conditions within the hearth have a direct impact on liquid drainage and hot metal quality. Consequently, the rate of carbon dissolution into liquid iron, and the factors contributing to the movement of liquids through the coke bed must be understood.

Investigations using quenched coke dissolution techniques have demonstrated that a mineral layer was formed between the liquid iron and the coke matrix as coke dissolves into iron under conditions comparable to the lower zone of the blast furnace hearth. This layer was predominantly comprised of calcium aluminates and was observed to change both its composition and morphology with time and temperature.

Based on these findings, and plant based observations of the Port Kembla blast furnaces, important phenomena such has hearth coke bed state (floating vs sitting) are able to be discussed in terms of a cleaning/fouling cycle contributed to by the formation of different calcium aluminates in the deadman, in turn influenced by the coke ash chemistry. Supporting arguments for each stage of the cycle are drawn from the fundamental research, plant based observation and detailed analysis of specific blast furnace events.

Application of this knowledge to Port Kembla blast furnace operations has allowed identification of periods where there is elevated risk of compromised hearth conditions. Further work in this area is expected to identify techniques that will allow a floating deadman to be secured improving furnace stability, iron quality and reducing hearth wear.

INTRODUCTION

The deadman is the packed coke bed in the lower zone of the Ironmaking blast furnace, occupying a region extending from the hearth up to the tuyeres and a roughly conical region above the tuyeres up into the bosh. It received its name for the very long residence times of coke within this region. Whether it floats (is in a dynamic state) or sits (is in a static state) in the hearth depends on the force balance between the buoyancy of the coke bed and the weight of the burden actually applied on the deadman (Vogelpoth,1985).

The internal condition of the hearth, and hence deadman state, is of critical importance to the stable operations of a blast furnace. The permeability of the hearth has a direct impact on gas and liquid passage through the lower zone of the furnace. The quality of the liquid iron is determined as the iron percolates through the packed coke bed in the deadman and hearth of the blast furnace (Omori, 1987). Damage to the hearth will limit campaign life as repairs cannot be undertaken without long stoppages. In practice, the blast furnace operator would like to avoid problems in the blast furnace hearth. Maintaining a dynamic, permeable deadman will significantly assist this aim.

Thus, from an operational point of view, it is essential to have knowledge of the state of the deadman to understand behaviour of the blast furnace hearth. Methods involving pressure probes installed in tapholes Havelange et al. (2004) have been employed for direct measurement of the deadman state, but such an approach is expensive and very restrictive as it removes a taphole from operation. It is widely accepted that monitoring the thermal cycles of thermocouples installed in the hearth and sidewalls of the furnace can be used to infer the deadman state. Lathelan et al. (1991) (Bonte & Huysse, 1999). Such an approach is based on the influence the deadman has on the flow of hot liquids within the hearth. Other indirect methods utilising hot metal and slag composition have been successfully employed in combination with monitoring the thermal cycles in the lower zones of the furnace to infer the state of the deadman. Nightingale et al. (2000) Brannbacka et al. (2007).

This article presents work undertaken at BlueScope Steel's Port Kembla blast furnaces, that has related newly available data on the composition and morphology of a coke ash mineral layer that can form as coke is dissolved in the liquid iron the hearth to the deadman state.

COKE ASH MINERAL LAYER

Information on what type of layer forms on the coke as the dissolution reaction proceeds comes from an excellent study by Gudenau et al. (Gudenau et al. 1990) who present data on the ash (mineral matter) found on the surface of coke particles dipped in liquid iron and from sessile drop studies. In other liquid iron sessile drop studies by Khanna et al. (2005), McCarthy et al. (2003) and Wu et al. (2000), a drop of liquid iron was reacted with a carbonaceous substrate. It was found that an ash (mineral) layer formed at the iron - carbonaceous material interface. General observations of the droplet surface in these studies indicated that the ash (mineral) layer at the interface was initially rich in Al_2O_3; however, as the reaction time increased, the proportion of CaO increased, in some cases in excess of that expected from coke ash composition alone Khanna et al. (2005). Sulfur was also observed to be concentrated at the interface as a complex iron, calcium sulfide.

Recent studies by the current authors ,Chapman et al. (2008) and Chapman et al. (2007) have related measurements and observations of the composition and morphology of the mineral layer formed at the coke-liquid iron interface to the rate of coke dissolution. It was found that the amount of material present in the mineral layer between the coke and liquid iron was observed to be increasing with reaction time. As the coke dissolution reaction continues the predominant structure changes from a loose agglomeration of primarily alumina particles to an open porous network of acicular needles as shown in

Figure 1. EDS analysis confirmed these needles are predominately CA6. On further dissolution the calcium enrichment of the mineral layer continues. The layer retains a relatively open structure however the fine needles evident in Figure 1 are replaced by a coarser structure as 2 dimensional plates of CA2 develop. As the dissolution reaction continues further, the calcium enrichment of the mineral layer also continues. The structure of the predominant mineral layer changes from being an open structure evident in Figure 1 to a dense layer that is well bonded to the iron surface as shown in Figure 2. EDS analysis confirmed the layer consisted of regions of CA2 and CA.

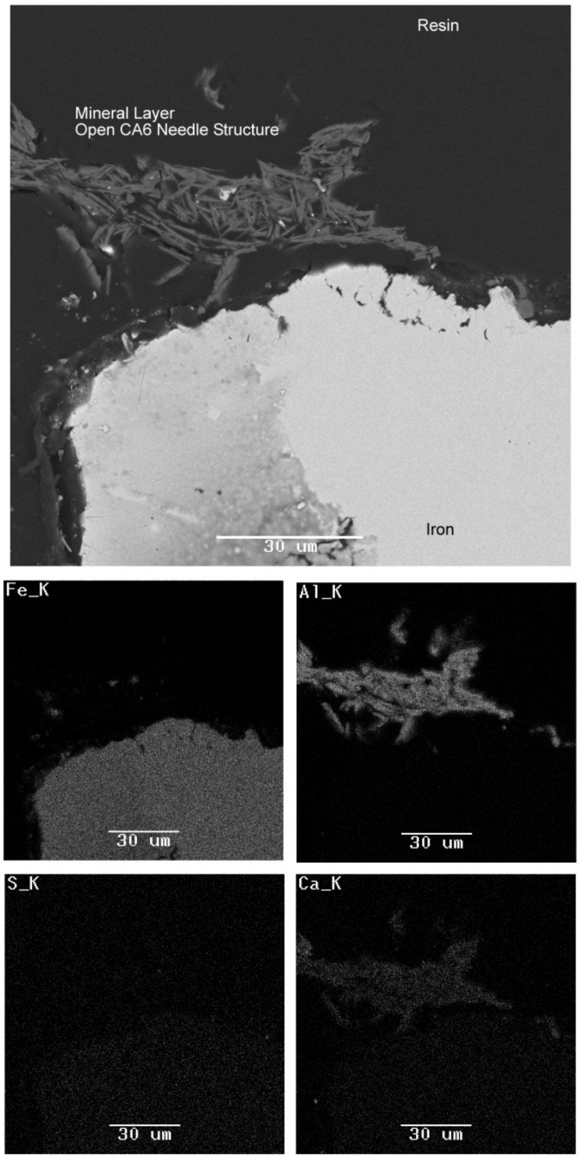


Fig. 1: SEM Backscattered electron images and elemental X-ray maps of mineral matter layer quenched after 2 minutes at 1500^{o}C. (Chapman et al. 2008)

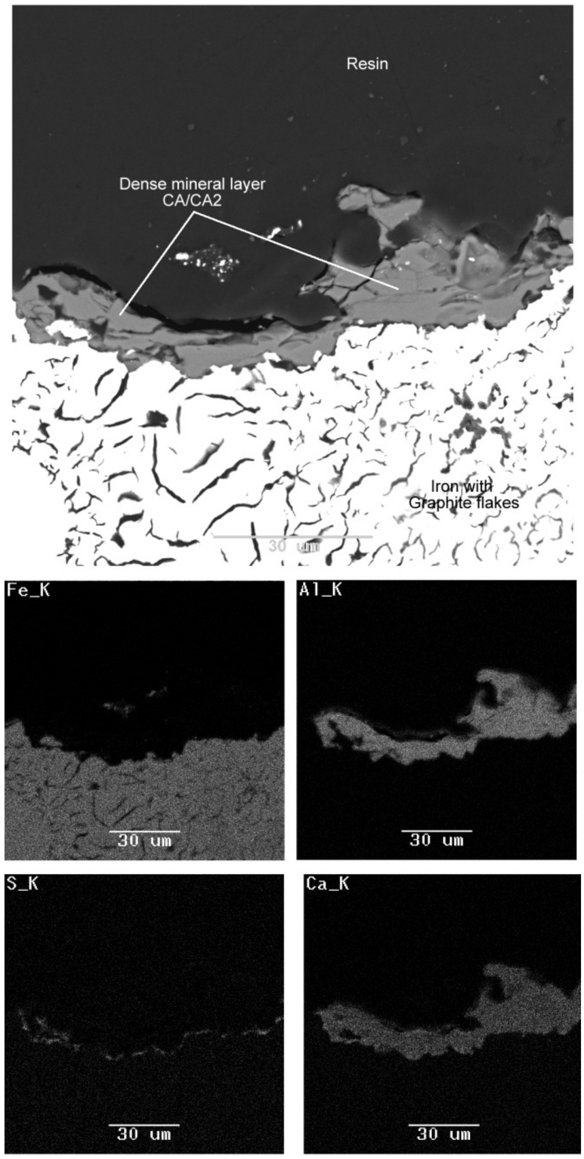
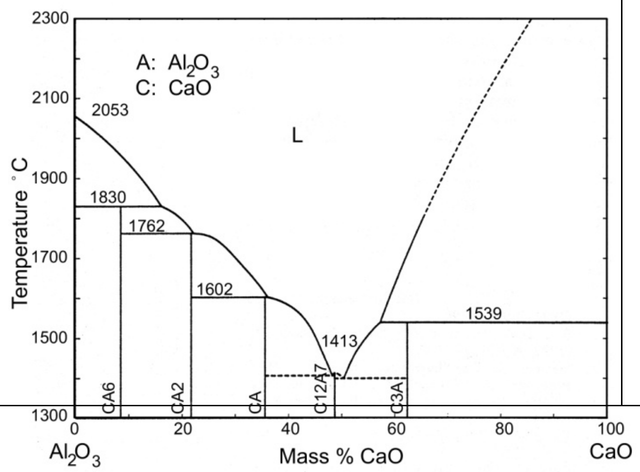


Fig. 2: SEM Backscattered electron images and elemental X-ray maps of mineral matter layer quenched after 60 minutes at 1500^{o}C. (Chapman et al. 2008)

The role of calcium enrichment in the mineral layer at the melt interface can be understood by considering the CaO-Al_2O_3 binary phase equilibria. There are three distinct calcium aluminates at the alumina rich end of this system as shown in the CaO-Al_2O_3 binary phase diagram in Figure 3.

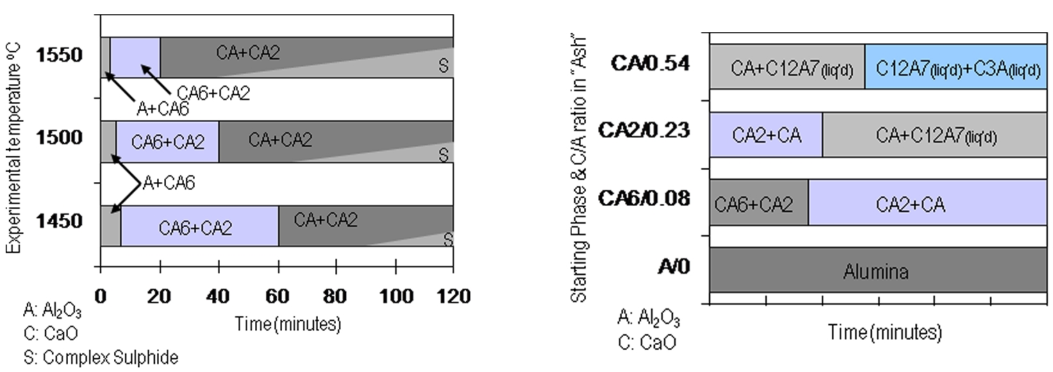


Phase represented on the Calcium-Alumina phases diagram

Al_2O_3	(A)
$CaO.6Al_2O_3$	(CA6)
$CaO.2Al_2O_3$	(CA2)
$CaO.Al_2O_3$	(CA)
$12CaO.7Al_2O_3$	(C12A7)
$3CaO.Al_2O_3$	(C3A)
CaO	(C)

Fig. 3: CaO-Al_2O_3 Phase Diagram (Lankford, 1985)

Figure 4(a) summarises the development of the coke-iron mineral layer in terms of its molar CaO- Al_2O_3 ratio. From Figure 4(a) it can be seen that calcium present in the mineral layer increases with temperature and reaction time.



(a) (b)

Fig. 4: a) Predominant mineral matter phase(s) at the coke – metal interface versus experimental time and temperature. b) Predominant mineral matter phase(s) at the coke – metal interface versus ash composition. (Chapman 2009)

This work also developed a coke analogue (Chapman, 2009) that had the key characteristics of coke, but could be manufactured to contain an ash of specified amount and composition. Figure 4(b) summarises the development of the coke-iron mineral layer produced from the coke analogues. From Figure 4(b) it can be seen that the calcium aluminate phases produced in the mineral are influenced by the initial composition of the coke ash, with higher initial CaO compositions promoting the appearance of the higher CaO calcium aluminate, C12A7, that could be liquid at ironmaking temperatures.

BLAST FURNACE DEADMAN STATES

A floating deadman can be characterised as in a dynamic state. Coke within the bed maintains some degree of motion as the bed rises and falls with the casting cycle and liquid levels within the hearth. In this state, debris within the bed can be floated out through the loosened coke bed and good permeability and high voidage in the bed is maintained. The high permeability of the dynamic deadman enables consistent drainage throughout the hearth as the liquid iron and slag can freely drain through the bed reducing circumferential flow and heatlaod on the sidewalls of the hearth. The presence of a coke free layer under the coke bed further reduces the need for the liquid to flow around the circumference of the hearth, but will increase the hearth refractory temperature.

In contrast, a deadman where the coke bed is sitting on the hearth can be characterised as a static state. Under such a state, residence time of the coke in the deadman increases significantly and movement is restricted. Debris is "trapped" and unable to float out of the bed, reducing permeability as it accumulates. The reduced permeability impedes liquid drainage through the deadman, forcing the liquids to circumference of the hearth, increasing wall temperature and refractory wear. As the flow of hot liquids is directed towards the hearth walls, temperatures within the deadman drop, and solidification of a material on the hearth may also occur.

Neither state can be maintained indefinitely as illustrated in Figure 5 which presents the thermal cycling of the hearth plug thermocouples in the No.6 Blast furnace at BlueScope Steel's Port Kembla works spanning 10 years from 2000 to 2010. Higher hearth plug temperatures are considered indicative of a dynamic state, while the low temperature are indicative of a static state. The overall upwards trend that is apparent in both the high and low temperature extremes is caused by gradual wear to the furnace's sacrificial hearth plug refractories.

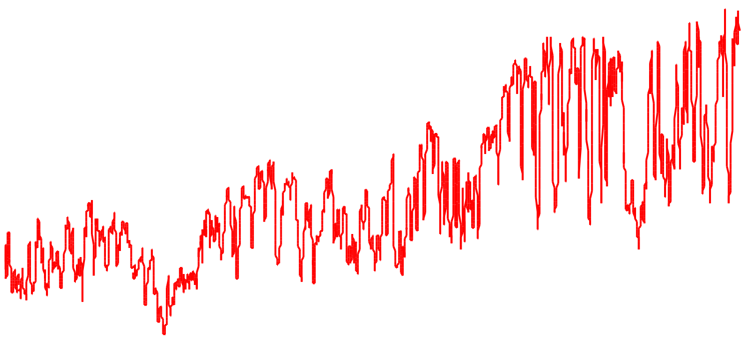


Fig. 5:

ALUMINA EFFLUX FROM THE BLAST FURNACE

Alumina efflux represents an alumina balance on the blast furnace. It is calculated as the ratio of alumina contained in the burden to alumina contained in the slag, expressed as a percentage. Thus a value less than 100% indicates that alumina is being accumulated inside the furnace and a value of over 100% indicates that more alumina than the burden contains is being removed from the furnace.

The transition from a dynamic to static deadman is generally a gradual transition. The transition from static to dynamic however can be a violent event, significantly impacting the stable operations of the furnace. Taphole length may decrease rapidly as accumulated clay masses are disturbed, while in extreme cases, damage may be caused to the tuyeres and tuyere coolers. During such a transition debris that had accumulated in the hearth is flushed out, reducing slag viscosity and adversely impacting liquid drainage from the furnace. Discharge of the debris from the hearth is irregular, and as presented in Figure 6, it may take many months to fully clean the accumulated debris from the furnace and restore the permeability of the hearth.

Figure 6, presents this alumina efflux along with the hearth plug temperature of the No.6 Blast furnace at BlueScope Steel's port Kembla works. During the period spanning August 2000 to March 2001 the plug temperature is observed to be falling, indicative of a static deadman state. Over this same period the alumina efflux is consistently less than 100%, indicating that alumina is accumulating in the blast furnace. For the remainder of 2001, the furnace suffered sustained low hearth plug refractory temperatures, indicating that the static deadman was continuing throughout this period, however the alumina efflux returned to a balanced position.

In November 2001 the transition from a static to dynamic deadmen state starts. A jump in hearth temperature is observed, and over the first half of 2002, the hearth temperatures are observed to be generally increasing. During this period, there is also an initial spike in the alumina efflux, followed by a gradual but consistent increase in the alumina efflux from the furnace. This is followed by a period of approximately 9 months of elevated alumina efflux from the furnace as the accumulated debris is flushed from the now dynamic deadman.

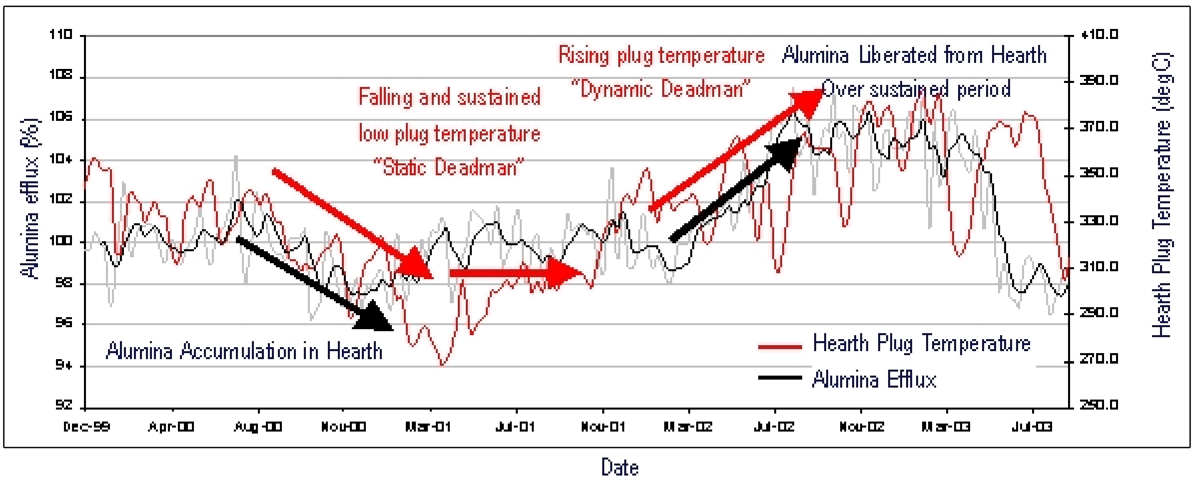


Fig. 6: Hearth Plug Temperature and Alumina Efflux from No.6 Blast Furnace

INFLUENCE OF COKE ASH CAO ON HEARTH BEHAVIOUR

The level and composition of coke ash in the blast furnace feed at Port Kembla has historically been very stable (see figure 7). Following extensive improvements in the coal preparation plants in the late 80's significant reductions in both coke ash and the level of CaO in the coke ash were achieved. This remained stable throughout the 90's. However, since 2000, there have been significant variations in coke ash.

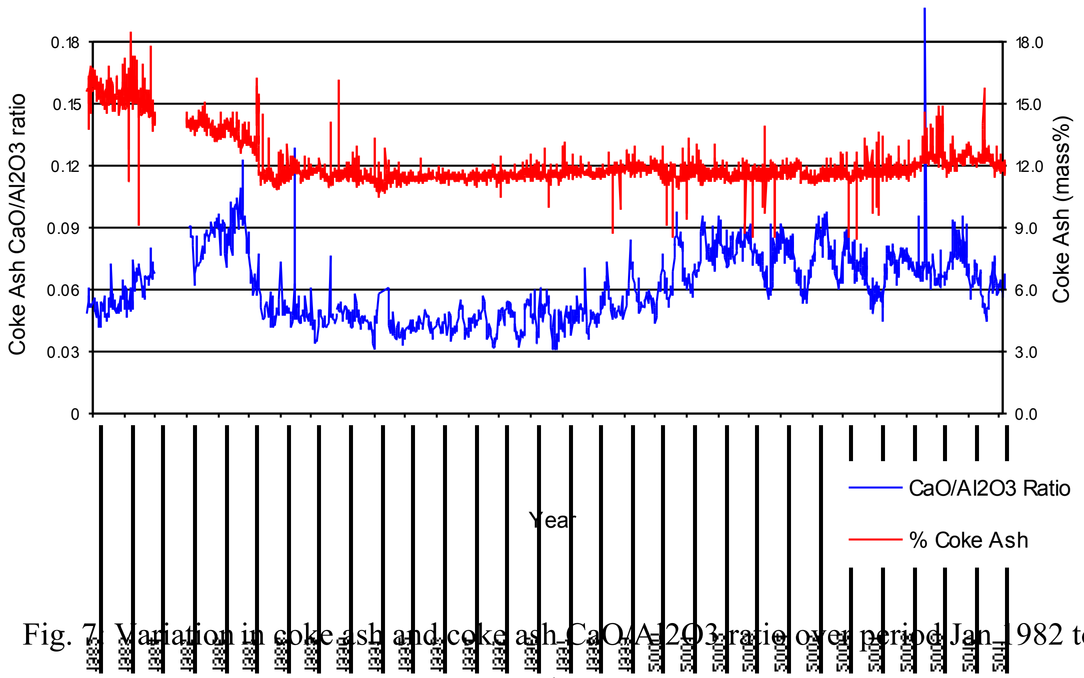


Fig. 7: Variation in coke ash and coke ash CaO/Al2O3 ratio over period Jan 1982 to March 2011

Figure 8 highlights the deadman response to the coke ash CaO, presented as the ratio of CaO/Al_2O_3 in the coke ash, during 1985-86. Following a relatively low value in March 1985, the coke CaO had been relatively high and stable until late 1986. The high and stable Coke CaO level saw the hearth plug temperature on the No.5 Blast Furnace (2nd Campaign) rise significantly in September 1985, indicating a change in deadman state from static to dynamic. This dynamic deadman state was maintained until the drop in coke ash CaO in late 1986 when the hearth plug temperatures also dropped indicating that the deadman condition had been compromised and was then in a static state. This was despite the accompanying drop in total coke ash.

From inspection of Figure 9, data from the latter part the No.5 BF 2nd Campaign, it is evident that with the sustained low coke ash CaO levels, a sustained dynamic hearth was not again achieved during the 2nd campaign.

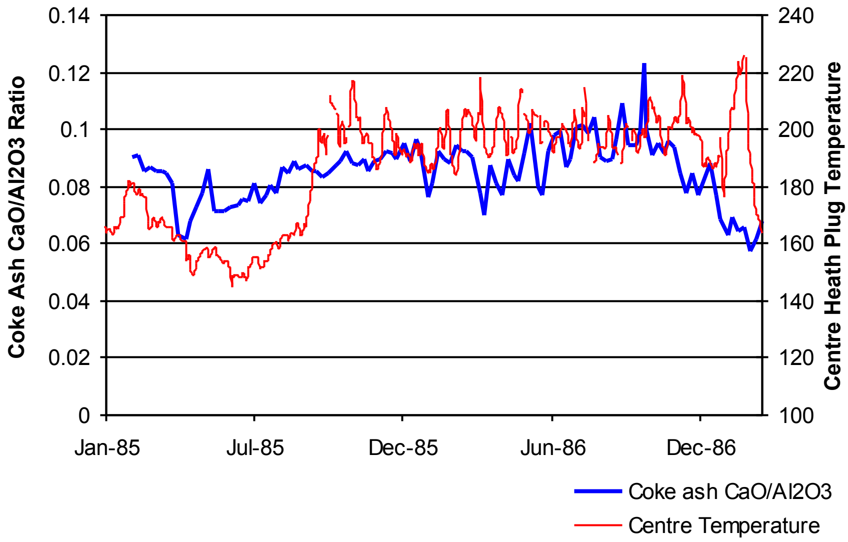


Fig. 8: No.5 Blast Furnace Centre Hearth Plug Temperature and coke ash CaO/Al_2O_3 ratio (mid 2nd Campaign)

Data presented in Figures 10 and 11 show a similar picture for the 3rd campaign of the No.5 Blast Furnace. In Figure 10, the hearth temperature cycle can be clearly observed to be following the CaO/Al_2O_3 ratio of the coke ash. This is particularly evident in both March 1996 and September 1996 where the CaO/Al_2O_3 ratio had fallen to historically low levels, apparently forcing the deadman into a static state each time. Similarly in Figure 11, illustrating the 2003 period, the CaO/Al_2O_3 ratio falls consistently from the start of the year from high levels in January 2003 to very low levels by September 2003, before rising to finish the year at a high level again. The hearth temperature indicates that the deadman has entered a static state from April, and has remained that way, before a rapid transitioning to a dynamic state in October 2003, approximately 1 month after the coke ash CaO had increased.

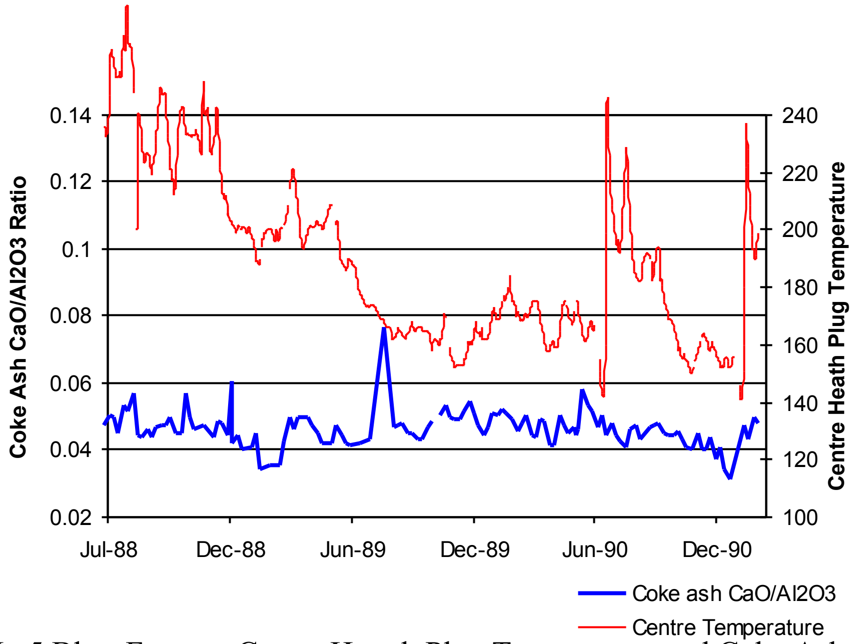


Fig. 9: No.5 Blast Furnace Centre Hearth Plug Temperature and Coke Ash CaO/Al_2O_3 ratio (End 2nd Campaign)

Fig. 10: No.5 Blast Furnace Centre Hearth Plug Temperature and Coke Ash CaO/Al_2O_3 ratio (3rd Campaign)

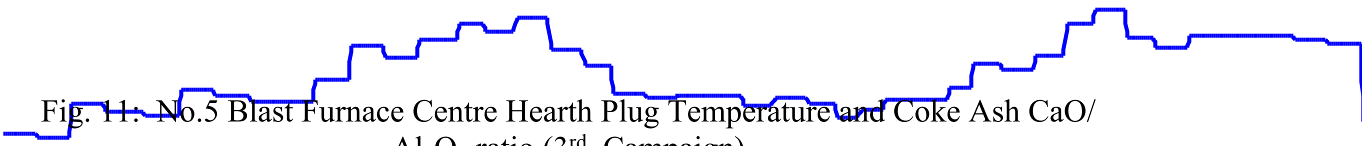


Fig. 11: No.5 Blast Furnace Centre Hearth Plug Temperature and Coke Ash CaO/ Al_2O_3 ratio (3rd Campaign)

The nature of the influence of the coke ash CaO level on the hearth behaviour is also evident at finer time scales. Figure 12 presents the hearth plug temperatures from the BlueScope Steel No.6 Blast Furnace at Port Kembla during 2006. This furnace does not have a single centre thermocouple, instead having a set of four near centre thermocouples.

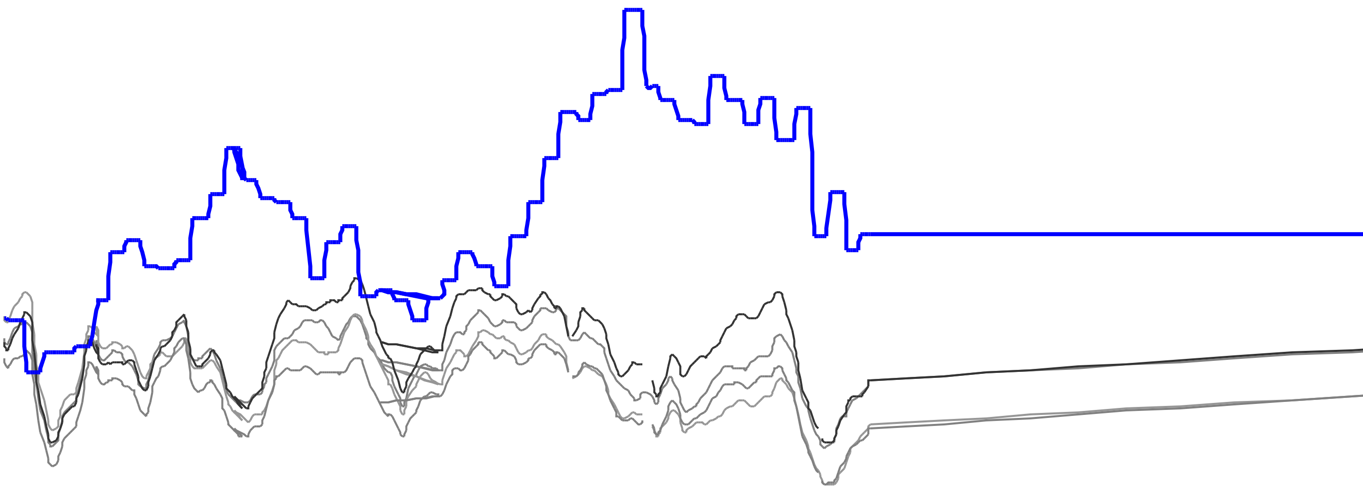


Fig. 12: No.6 Blast Furnace Centre Hearth Plug Temperature and Coke Ash CaO/Al_2O_3 ratio during 2006

Early in 2006 the coke ash CaO/ Al_2O_3 ratio was relatively high, around 0.08. It is evident that during the first half of 2006 the transitions between deadman states (Static and Dynamic) were relatively smooth. By contrast, by the end of 2006, the coke ash CaO/ Al_2O_3 ratio has dropped to a very low level, and the smooth transitions between deadman states is no longer evident. Instead, the hearth plug thermocouples are displaying a very rough rapidly changing trend, and transitions between deadman states appear to be delayed, indicating that the hearth condition has been altered, in fact compromised.

Figure 13 illustrates a method of assessing the roughness of the hearth refractory temperature trends. The period between a change in the rate of plug temperature change may be calculated as the time between a change in sign of the 2nd derivative of the hearth plug temperature, shown as X and Y in Figure 13. For a "smooth" trend, this period between changes, shown as X, is larger than for a "rough" period, Y.

In Figure 14, this measure of trend roughness (average period between a change in the rate of plug temperature change) is plotted (as days) against the coke ash CaO/ Al_2O_3 ratio. This indicates that low coke ash CaO/ Al_2O_3 ratio promotes disruption in the thermal cycling of the hearth plug temperatures, inferring a disruption of the internal condition of the deadman.

It is our belief that the influence coke ash CaO/ Al_2O_3 ratio has on the behaviour of the blast furnace hearth can be explained by considering the nature of the mineral layer that is formed as the coke is dissolved into the liquid iron in the hearth of the blast furnace. Figure 4 summarised the form of calcium aluminates that were found to form during coke dissolution in the laboratory. It is reasonable to assume that similar phenomena can occur in the blast furnace hearth, below the slag level. Thus a coke with a low CaO/ Al_2O_3 ratio ash would promote the formation of the calcium aluminates that are alumina rich. These are Alumina and CA6. As shown in Figure 1 and Figure 3, these are very refractory in nature and consist of an acicular, needle like, structure. Such refractory debris in the hearth would not be likely to melt, and would also be unlikely to float easily out or the coke bed. The morphology of this ash resident in the deadman would also be likely to "trap" other fine debris like a filter and prevent it from being removed from the coke bed, further reducing the permeability of the deadman.

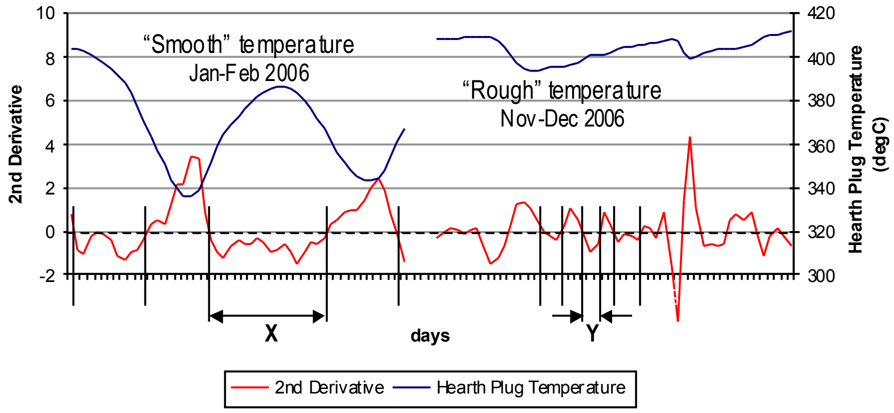


Fig. 13: Using the 2nd Derivative of the hearth plug refractory temperature to infer roughness of the temperature trend of No6 Blast furnace.

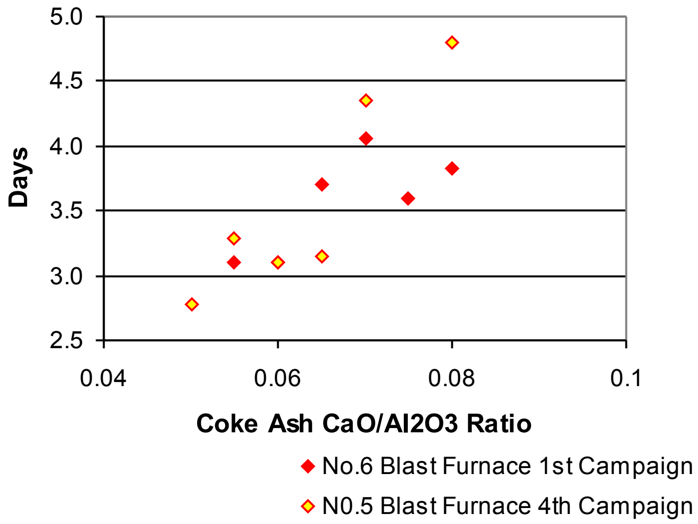


Fig. 14: Days between changes in the rate of Hearth Plug Temperature Trends against Coke Ash CaO/Al_2O_3 ratio on No.6 Bf and No.5 BF's 4th Campaign

In contrast, a coke with a higher CaO/Al_2O_3 ratio ash would promote the formation of the higher calcium, calcium aluminates. These are the CA2, CA and possibly C12A7 phases. As shown in Figure 2 and Figure 3, these are much less refractory in nature and consist of a dense blocky structure instead of the acicular structure of CA6. Ash residue consisting of these materials would be more likely to melt at ironmaking temperatures and be more readily floated out of the deadman coke bed. In addition the blocky morphology of these phases are less likely to trap other forms of debris in the deadman coke bed.

CONCLUSIONS

By combining new knowledge obtained in fundamental laboratory studies with plant data that spans multiple furnaces and furnace campaigns, we have extended our understanding of blast furnace hearth behaviour.

The refractory nature of residual coke ash in the blast furnace hearth compromises the hearth condition, and therefore blast furnace operations.

Relatively minor (and therefore not considered) components in feed materials can have a significant impact on the daily operations and ultimately campaign life of the blast furnace.

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BRIEF BIOGRAPHY OF PRESENTER

Michael has been working at BlueScope steel for over 20 years. During this time he has worked in both operations and technical roles in both the steelmaking and more recently iromaking departments. In 2009 Michael completed his PhD titled "Insoluble oxide product formation and its effect on coke dissolution in liquid iron", a project that was jointly funded by the ARC and Bluescope Steel.