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Melting Behaviour of Iron Ore Pellet Bed under Nut Coke Mixed Charge Conditions

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The melting and dripping behaviour of an iron ore pellet bed mixed with nut coke are investigated through a series of quenching, melting and dripping experiments. In the melting bed of iron ore pellets, nut coke acts as a frame to maintain the passage for the gas flow. The iron carburisation level of the pellet shell is found to control the melting temperature of the pellet bed. Simultaneous and layer-wise melting is observed for the pellet bed with and without mixed nut coke, respectively.

In the case of pellet bed mixed with nut coke, the liquid dripping starts at a lower temperature (1 500°C) compared to the case when nut coke is absent (1 518°C). Subsequently, a steady rate of liquid dripping is observed for the pellet bed mixed with nut coke. However, in the case of the pellet bed without nut coke, most of the liquid drips (~50 wt%) at high temperature (1 550°C). The difference in carbon content of the quenched pellets and the dripped metal reveals that a substantial iron carburisation occurs when liquid iron flows over the regular coke particles.

The nut coke is noticed to consumed preferentially in place of the regular coke. Additionally, the total coke consumption decreases with an increase in nut coke addition in the pellet bed. These results give support for more extensive use of nut coke as a replacement of the regular coke in the ironmaking blast furnace.

KEY WORDS: ironmaking; blast furnace; nut coke; pressure drop; iron carburisation; melting; dripping.

1. Introduction

Steel is an essential material for the development of a sustainable society. The steel demand is expected to rise up to 2.5 billion ton per annum by 2050,1) which is twice the current global consumption level. The pig iron (with 3.50–4.50 wt%C) primarily produced by the blast furnace is expected to be utilised for steel (with 0.05–2.14 wt%C) production to meet this future demand.2) However, considering the carbon intensive nature of iron making from the blast furnace route, process enhancement is a need to improve sustainability.

The blast furnace is a countercurrent reactor, its energy efficiency and productivity depends strongly on the gas permeability.3) In the cohesive zone, the gas permeability is significantly hindered by the softening and melting of the ferrous raw materials.3,4) Therefore, to improve the gas permeability in the cohesive zone, it was suggested to mix-charge the ferrous burden (pellet, sinter and iron ore) with small-sized coke (indicated as nut coke, with dimensions 8–40 mm).5) This has provided an opportunity to use undersize coke, which is generated due to the strict regular coke size (40–80 mm) demand from the blast furnace. Furthermore, nut coke utilisation in the blast furnace is envisaged to increase the Thermal Reserve Zone (TRZ) length,6) promote shaft efficiency,7,8) enhance reduction kinetics,9,10) and improve softening and melting properties.11,12)

In spite of its advantages, in the blast furnaces around the world, the nut coke is utilised only in a limited amount (less than 30 wt% of the total coke rate).13,14) The nut coke utilisation is driven by its generation during the coke making process and as yet no additional efforts have been made to enhance the use. Furthermore, it was reported that for good permeability at least 2 to 3 discrete layers of regular coke particles are required inside the blast furnace.4,15) Although these studies were not performed in the light of nut coke utilisation, experimental research indicates that regular coke thinning will have a negative impact on the overall gas permeability.15) Since the idea of nut coke use is as the replacement of regular coke; it is of utmost importance to understand the effect of the nut coke use on the bed permeability.

Therefore, in our previous study,16) a thorough investigation was performed to understand the physicochemical behaviour of the pellet bed when nut coke (0–40 wt%) was added as a replacement of the regular coke. It was found

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that the nut coke addition in the pellet bed improves the bed permeability substantially.[16] Furthermore, the cohesive zone temperature range was observed to reduce by 16°C for every 10 wt% nut coke addition.[16] In the study, it was suggested that along with enhanced reduction kinetics, the higher iron carburisation would be the main cause for such behaviour. However, the complete characterisation was not presented and discussions were not made about melting pattern in the presence or absence of nut coke in the pellet bed.

Nut coke addition, on the one hand, provides multiple contact points of coke with the ferrous raw material; on the other hand, the regular coke layer becomes thin due to the replacement. This will have an impact on the melting and dripping pattern of the liquid from the ferrous bed. To understand the dripping behaviour some simulation studies[17–19] have been performed. However, in these studies either nut coke addition was not considered or the chemical interaction (reduction of FeO slag and iron carburisation) at the time of melting and dripping was ignored, which makes these studies of limited use.

In the present study, a thorough investigation is performed to understand the effect of nut coke addition on the melting and dripping behaviour of the iron ore pellet bed. The study is extended to examine the effect of nut coke addition on the iron carburisation, in both solid and liquid state. Furthermore, the level of coke (nut coke and regular coke) consumption is discussed for the cases when nut coke is added to the pellet bed as a replacement of regular coke.

2. Materials and Method

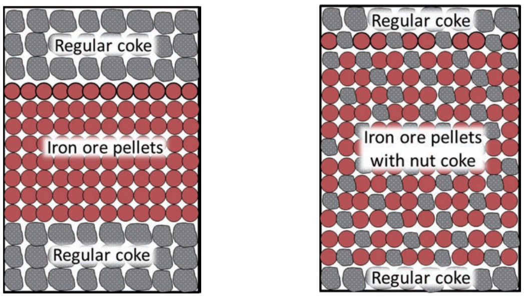
2.1. Raw Materials

Commercially supplied olivine fluxed iron ore pellets and nut coke of size range of 10 to 13 mm and 10 to 15 mm, respectively, are utilised in the present study. The nut coke size of 20 to 25 mm is applied as the regular coke due to the crucible size limitations (inner diameter 64 mm). The chemical analysis of the pellet is given in **Table 1**.

Figure 1 depicts a schematic of the sample bed arrangement inside the graphite crucible. In the sample without nut coke mixing, the pellet layers are sandwiched between the two regular coke layers (Fig. 1(A)). In the case of samples mixed with nut coke, the regular coke layer is proportionally reduced. As a result, the layer thickness of the regular coke decreases (Fig. 1(B)). In the experiment with nut coke, a maximum of 40 wt% replacement is used in the mixture to avoid critical thinning of the regular coke layers.

Table 1. Chemical analysis of the olivine fluxed iron ore pellets (XRF).

Species	Fe (total)	SiO_2	MgO	Al_2O_3	CaO	MnO	TiO_2	Basicity, B_4
Wt%	64.94	3.70	1.21	1.06	0.37	0.30	0.26	0.33



(A). Sample bed without nut coke. (B). Sample bed with mixed nut coke.

Fig. 1. Schematic of the sample bed arrangement inside the crucible. (Online version in color.)

All experiments are carried out with a constant bed mass of the pellet (500 g) and the coke (100 g), which represents a coke ratio of 300 kg/t of hot metal (kg/tHM) in the blast furnace equivalent. The blast furnace is assumed to operate with a pulverised coal injection (PCI) rate of 200 kg/tHM.

2.2. Experimental Conditions

A specially designed Reduction Softening and Melting (RSM) furnace (**Fig. 2**) is utilised to perform the experiments under simulated blast furnace conditions. Detailed information about the experimental set-up can be found in the references.[11,12]

The thermal and gas composition profiles followed during the experiments are derived from vertical probing of the real blast furnace.[20] A load of 0.98 kg/cm^2 (96 kPa) is applied on the top of the sample bed to mimic the blast furnace load condition. A displacement transducer (RDP, ACT2000C) and a differential pressure transducer (Honeywell, KZ) were applied for the measurement of the bed contraction and gas pressure drop across the bed, respectively.

For detailed investigation on the melting and dripping behaviour of the nut coke mixed pellet bed, the following three sets of experiments were performed. The methods are

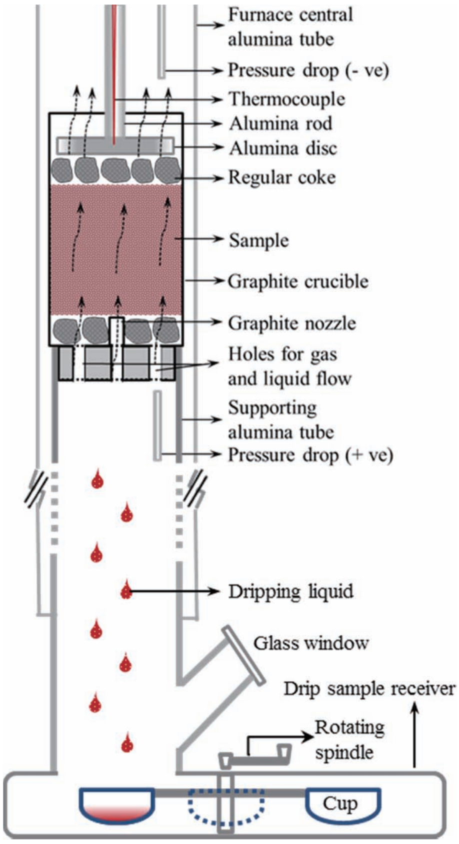


Fig. 2. Schematic of the RSM furnace, sample arrangement and dripped liquid collection system. (Online version in color.)

discussed below.

2.2.1. Melting Experiments

Full-scale high temperature (20–1 550°C) experiments were carried out in the RSM to realise the reduction and melting of the ferrous raw material. The thermal and gas profile followed during the melting experiments are given in **Table 2**. The liquid (metal and slag) drops are collected in cups located in the sample collector at the bottom of the RSM (Fig. 2). The event of first liquid dripping (at temperature T_{xf}) is recorded after visualising the droplet from the glass window (**Fig. 3**) located at the lower part of the RSM apparatus. The melting experiments were performed for different nut coke concentrations from 0 to 40 wt% at intervals of 10 wt%. Additionally, all melting experiments were repeated, to check the reproducibility.

The collected samples in the cups were excavated. Thereafter, a portion of the sample is pulverised to magnetically separate metal from slag. The slag composition (non-magnetic portion) is analysed by X-ray fluorescence (XRF), and the metal (magnetic portion) composition is analysed by LECO (Carbon-Sulphur analyser) for the carbon content.

2.2.2. Quenching Experiments

The quenching temperature for the sample bed was determined based on a series of high-temperature experiments.[16] In order to understand the prime reason of the pellet bed melting, samples were quenched from a temperature close to the bed melting temperature. In addition, to understand the liquid flow behaviour in the presence of nut coke, the sample bed was quenched around the dripping temperature.

For the case of pellet bed without mixed nut coke, the bed was heated to 1 480°C by following step 1 to 6 as shown in Table 2. Once this temperature was attained, the bed was quenched by purging nitrogen gas (7.5 litre per minute) and switching off the furnace heating. The sample bed mixed with nut coke was heated up to 1 450°C and 1 500°C by following steps 1 to 5 and 1 to 7 (Table 2), respectively, and then quenched by purging nitrogen gas (7.5 litre per minute) and switching off the furnace heating. After cooling, the sample crucibles were removed from the furnace and embedded in cold mounting polymeric resin and cut vertically into two halves for further analysis.

Table 2. Thermal and gas profile followed during the experiments.

Step	Temperature range (°C)	Heating rate (°C/min)	CO (%)	CO_2 (%)	H_2 (%)	N_2 (%)	Gas flow rate (litre/minute)
Step 1	20–400	7.0	0	0	0	100	5
Step 2	400–600	5.0	25	20.5	4.5	50	15
Step 3	600–950	5.0	30	15.5	4.5	50	15
Step 4	950–1 050	1.2	33	12.0	5.0	50	15
Step 5	1 050–1 450	5.0	42	0	8.0	50	15
Step 6	1 450–1 480	5.0	42	0	8.0	50	15
Step 7	1 480–1 500	5.0	42	0	8.0	50	15
Step 8	1 500–1 550	5.0	42	0	8.0	50	15
Step 9	1 550–20	−5.0	0	0	0	100	5

Fig. 3. The event of liquid dripping, viewed from the glass window located at the lower part of the RSM furnace. (Online version in color.)

2.2.3. Dripping Experiments

The thermal and gas profile during the dripping experiments was kept the same as for the melting experiments shown in Table 2. During the dripping experiments, the rotating sample collector located at the bottom of the RSM (Fig. 2) was utilised. The sample collector is fitted with multiple cups (12 pieces), which was rotated to collect the dripping liquid (metal and slag) over the time and temperature range. To compare the effect of nut coke addition, one experiment without nut coke and another with 40 wt% nut coke replacement ratio were performed.

After the melting and dripping experiments, the coke present inside the crucible was collected and sorted. The size difference between the regular coke and nut coke was utilised for the separation. Then the collected coke was weighed to estimate the amount utilised during the experiments.

2.3. Analysis

The cross-sections of the selected pellets were visualised by using an optical microscope (Keyence VHX-5000). The chemical composition of the pellets, dripped metal and slag were measured by X-ray fluorescence (XRF, Panalytical, Axios Max).

The elemental (iron and carbon) distribution present in the quenched sample were investigated[21] with the help of the Electron Probe Micro Analysis (EPMA- JEOL JXA 8900R). For an estimation of carbon content in the dripped metal, the combustion infrared detection technique (LECO, CS744) was employed.

3. Results and Discussion

In the stationary bed of the sample, the blast furnace conditions are simulated by varying the temperature and gas composition with time (Table 2). In the RSM, the ferrous oxide in the sample reduces, softens and melts to drain out of the bed. A profile of typical pressure drop curve during the pellet melting and dripping is shown in **Fig. 4** and critical process parameters are described in **Table 3**. During pellet melting significant bed deformation occurs, which results in filling of the interstitial voids. Consequently, a sharp rise in the pressure drop occurs across the bed (Fig. 4). Thereafter, the liquid fills up the voids to cause the maximum pressure drop (P_{Peak}). Then, the liquid starts to drip out (T_{xf}) providing pores for the recovery of the pressure drop.

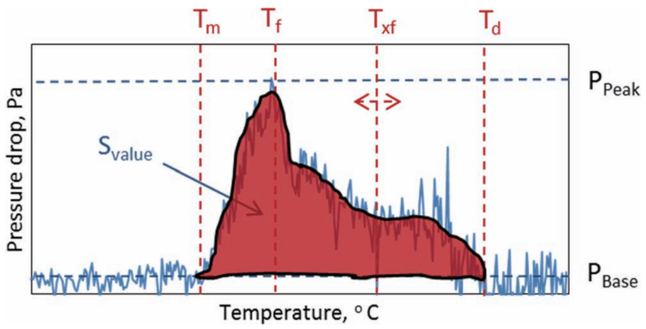


Fig. 4. A typical pressure drop curve during melting and dripping of the iron ore pellets in the bed. (Online version in color.)

Table 3. Process parameters derived from the pressure drop curve during the sample bed heating in the RSM.

Symbol	Description	Unit
T_m	The melting point of the sample bed, the temperature at which the pressure drop in the bed starts to increase steeply.	°C
T_f	The flooding point, the temperature at which the pressure drop reaches the maximum.	°C
T_{xf}	The first liquid drop point, the temperature at which the first liquid drop is observed from the glass window in RSM (Fig. 3).	°C
T_d	The dripping point, the temperature at which the pressure drop value reaches back to the base value as before the softening and melting.	°C
P_{Base}	The base value of the pressure drop before the melting phenomenon.	Pa
P_{Peak}	The peak value of the pressure drop, the maximum pressure drop value during softening and melting.	Pa
S_{value}	The area under the pressure drop curve, a measure of resistance to the gas flow during melting and dripping.	Pa.°C

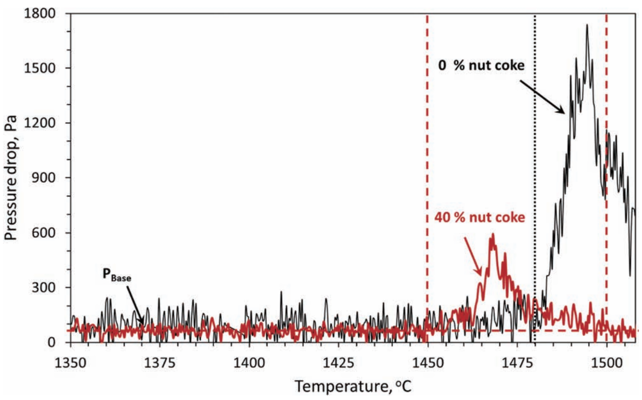


Fig. 5. Pressure drop curves and identified quenching temperatures for the sample bed without (quenched at 1 480°C) and with (40 wt%) mixed nut coke (quenched at 1 450°C and 1 500°C). (Online version in color.)

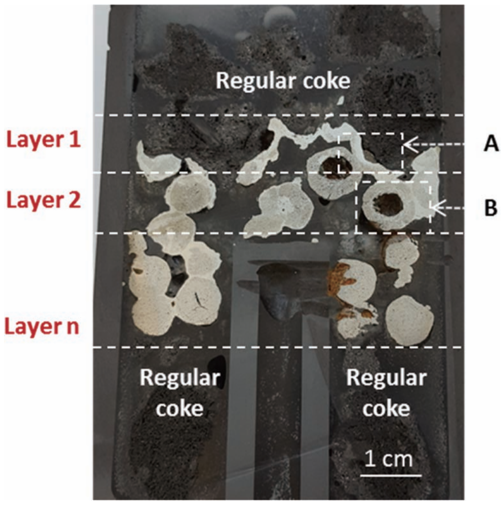


Fig. 6. Sample bed without nut coke quenched at 1 480°C. (Online version in color.)

3.1. Effect of Nut Coke Addition on the Pressure Drop

The effect of nut coke addition on the pellet bed contraction and pressure drop was discussed comprehensively in our previous article.[16)] In the present study, the fundamentals of pellet bed melting and dripping are investigated.

The pressure drop curves for the sample beds without nut coke and with 40% nut coke are shown in **Fig. 5**. It is observed that upon nut coke addition, the maximum pressure drop decreases and shifts towards lower temperatures. In order to investigate the prime reasons for such behaviour, iron ore pellet beds are quenched at various key temperatures. The pellet beds with and without mixed nut coke are quenched close to the bed melting temperatures, *i.e.*, 1 450°C and 1 480°C, respectively. To further investigate the effect of nut coke addition on the sample chemistry during dripping, the bed (with 40 wt% nut coke) is quenched at 1 500°C.

3.2. Pellet Bed in the Absence of Nut Coke

The cross-section of the sample bed without nut coke, quenched at 1 480°C is shown in **Fig. 6**. The layer arrangement of the reduced pellets is apparent from the photograph (layer 1 to layer n). In earlier work,[16)] it is suggested that the start of pellet bed melting is the prime reason for the sharp rise in the pressure drop. The broken top layer of pellets in the present experiment (Layer 1 in Fig. 6) suggests that melting has just started in the pellet bed. On the other hand, the pellets located in other layers are not broken and retain their shape. It also appears that after breaking the top layer of pellets, the regular coke layer from the top lowers into the second layer of pellets.

The layer interface between the regular coke layer and the broken pellet layer was visualised with the optical microscope. In the region A (Fig. 6), a clear wetted interface between the coke and pellet can be seen (**Fig. 7**). It appears that the regular coke indents the pellet shell present in the first layer (Layer 1). As a consequence, the pellets have apparently lost their strength under direct contact with the regular coke. The iron (pellet shell) carburisation occurs under direct contact with the regular coke, which results in the local melting breaking of the pellets.

To check the level of iron carburisation on the selected pellet of the first layer, EPMA point and area analyses are performed (Fig. 7). The numbers next to the points (**o**) in Fig. 7(a) represent the carbon content (in wt%) present at the examined spots (0.2 μm^2). For most of the spots, the present carbon is in range of 0.20 wt% to 0.40 wt%. However, for some sites, the carbon concentration is as high as 1.73 wt%. Therefore, to investigate the reason for the variation in the carbon distribution, an EPMA scan is performed on selected areas (Figs. 7(a) and 7(b)). This reveals that the carbon is present in diverse range (0 to 1.25 wt%) inside the iron matrix. Some spots of very high carbon concentration (> 2 wt%) can also be observed inside the pores, which is due to the presence of mounting resin. Nevertheless, the carbon is mostly distributed in similar range (~0.30 wt%) in the iron matrix as examined by point analysis.

A similar analysis is performed on the pellet selected from the Layer 2 (Fig. 6, region B). The carbon concentration obtained by EPMA (**Fig. 8**(a)) are approximately 0.03 wt%. In the second layer pellet, the carbon concentration is significantly less (8–10 times) than in the first layer. The EPMA elemental area analysis (Fig. 8(b)) further confirms the results from the point analysis. However, in the small areas close to the surface or in pores, the carbon is distributed in higher concentration (B1, B2 and B3) due to the presence of polymeric mounting resin (Fig. 8(b)). Grossly, the carbon concentration is observed significantly lower than in the pellet from the first layer.

The differences in carbon content on the reduced iron of the pellet in the first and second layer demonstrate that iron matrix carburisation results from direct contact with the regular coke. Subsequently, based on the iron carburisation level, melting of the first layer pellet occurs. After melting of the first pellet layer, the interface between the regular coke and pellet moves to the second layer for further iron carburisation and melting thereafter. Consequently, in the pellet bed without mixed nut coke, layer-wise melting occurs. These phenomena continue until all the pellets become molten and drip out of the sample bed (layer 1 to layer n, Fig. 6).

3.3. Pellet Bed Mixed with Nut Coke

3.3.1. Pellet Bed Quenched from 1 450°C

It is observed that the pellet bed melting temperature decreases with the nut coke addition (Fig. 5).[16] In order to investigate the principal reason for decrease in the bed melting temperature, pellet bed mixed with nut coke (40 wt%) is quenched close to the bed melting temperature of 1 450°C. The cross section of the quenched sample bed with 40 wt%

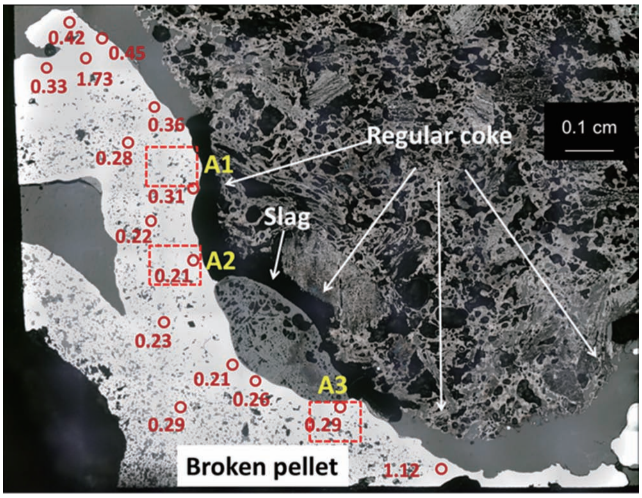
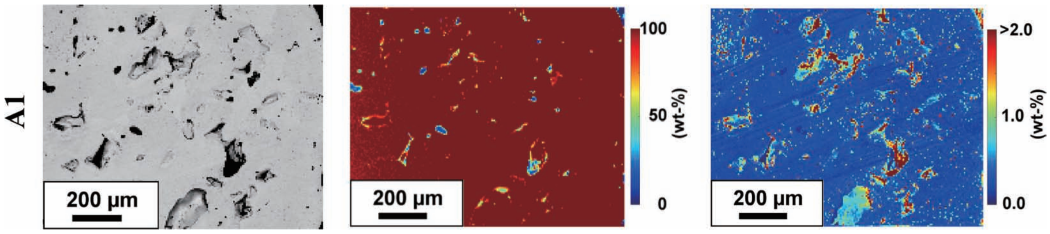


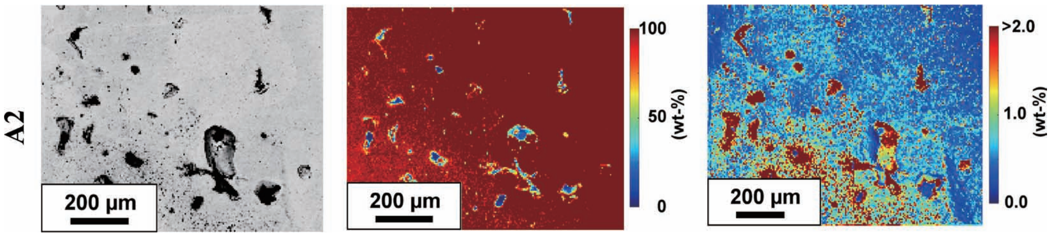
Fig. 7(a). Micrograph of the region A selected from pellet bed without nut coke, quenched at 1 480°C (broken first layer pellet, Fig. 6). (Online version in color.)



(a). Back scattered electron image

(b). Iron distribution (EPMA)

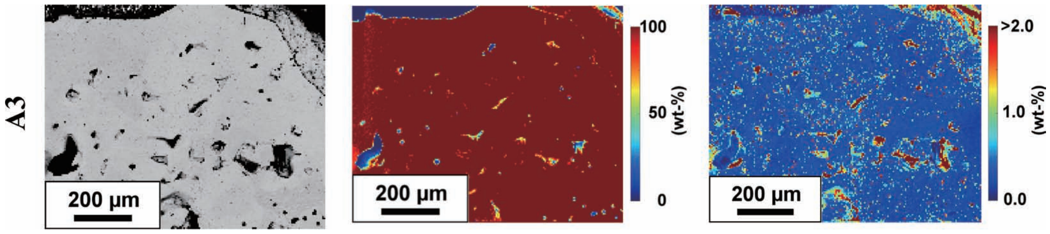
(c). Carbon distribution (EPMA)



(d). Back scattered electron image

(e). Iron distribution (EPMA)

(f). Carbon distribution (EPMA)



(g). Back scattered electron image

(h). Iron distribution (EPMA)

(i). Carbon distribution (EPMA)

Fig. 7(b). EPMA area scan at location A1, A2 and A3 from Fig. 7(a). (Online version in color.)

mixed nut coke is shown in **Fig. 9**. From the photograph, it is apparent that the nut coke acts as a frame to support the bed structure by physically hindering the sintering among the pellets.[22] Thus, the pores are instrumental for the gas to flow in the pellet bed during melting. It is also noted that most of the pellets are deformed, especially the pellets located close to the coke (nut coke and regular coke). This is due to the start of melting in the bed.

From the quenched pellet bed a representative pellet is selected (**Figs.** 9 and **10**) to examine the effect of nut coke addition on the pellet chemistry. The EPMA point analysis on the pellet reveals a wide variation (0.00–1.26 wt%) in carbon content. Nevertheless, the average carbon concentration is observed to be higher than in the case where nut coke is absent in the pellet bed. To further investigate this phenomenon, pellet areas are scanned for the presence of carbon (Figs. 10(a) and 10(b)). In the peripheral region (C1 and C3), the segregation of carbon is noticed in the form of grains; the carbon concentration is found distributed in range 0.60 wt%–0.80 wt% in the matrix of iron (Fig. 10(b)). The area around the pellet core is also reduced. However,

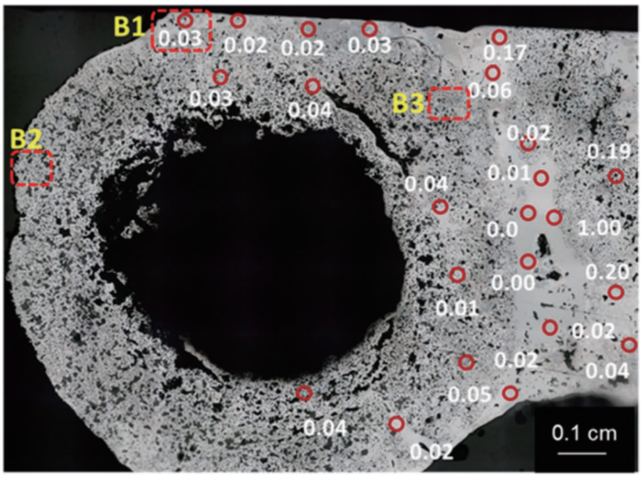


Fig. 8(a). Micrograph of the region B selected from the pellet bed without nut coke, quenched at 1 480°C (second layer pellet, Fig. 6). (Online version in color.)

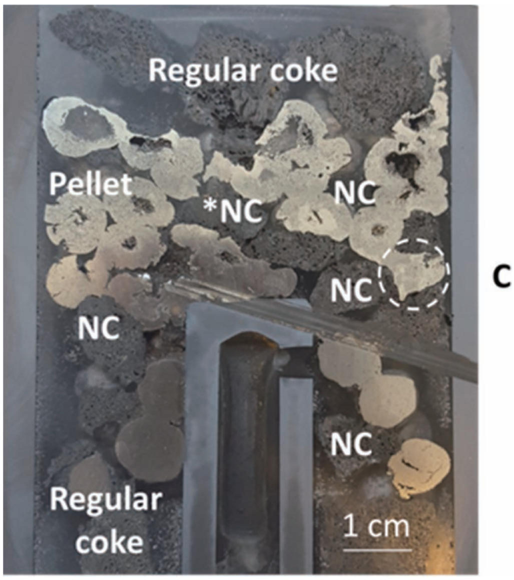
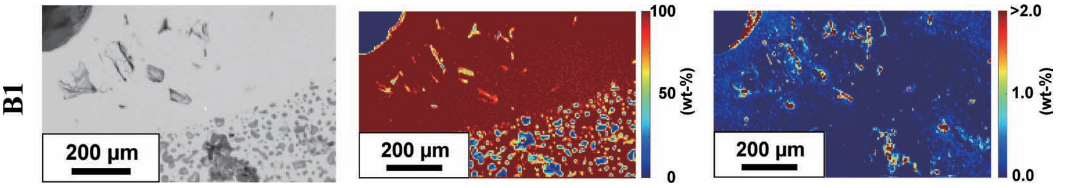


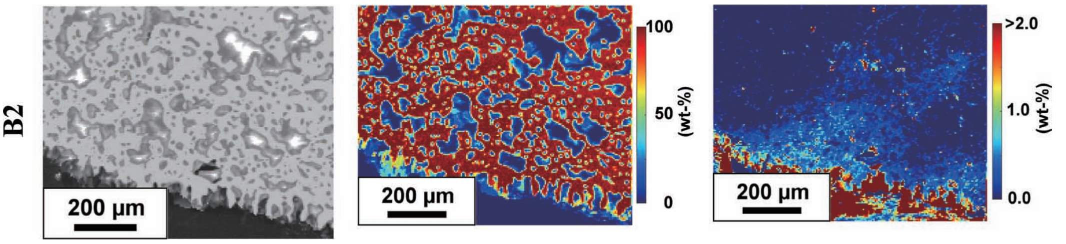
Fig. 9. Sample bed with nut coke (40 wt%) quenched at 1 450°C. (Online version in color.)



(a). Back scattered electron image

(b). Iron distribution (EPMA)

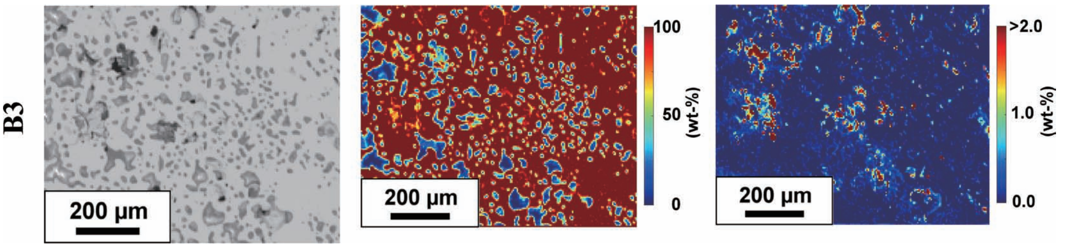
(c). Carbon distribution (EPMA)



(d). Back scattered electron image

(e). Iron distribution (EPMA)

(f). Carbon distribution (EPMA)



(g). Back scattered electron image

(h). Iron distribution (EPMA)

(i). Carbon distribution (EPMA)

Fig. 8(b). EPMA area scan at location B1, B2 and B3 from Fig. 8(a). (Online version in color.)

the carbon concentration is observed to be insignificant (~0.00 wt%, C2). This suggests that similar to the reduction reactions, the iron carburisation also progresses topochemically in the reduced pellets.

In the pellet bed mixed with nut coke, the CO-rich gas is able to flow inside the bed, invoking a higher level of carburisation of the pellets.[23] Additionally, by direct contact of the pellet iron shell with coke (regular coke and nut coke), iron carburisation occurs. As a result, the pellet shell starts to melt and loses its shape at many spots inside the bed (Fig. 9). Thus, in the pellet bed mixed with nut coke, simultaneous iron carburisation occurs. It results in simultaneous melting in the pellet bed mixed with nut coke contrary to the layer-wise melting in the absence of nut coke.

3.3.2. Pellet Bed Quenched from 1 500°C

In the case of nut coke mixed pellet bed, lower rate of bed deformation is noticed during the melting and dripping stage (third stage of bed contraction).[16] The sample bed is quenched at 1 500°C to investigate the effect of nut coke addition during simultaneous melting and dripping (**Fig. 11**). Nut coke supports the bed structure to resist the defor-

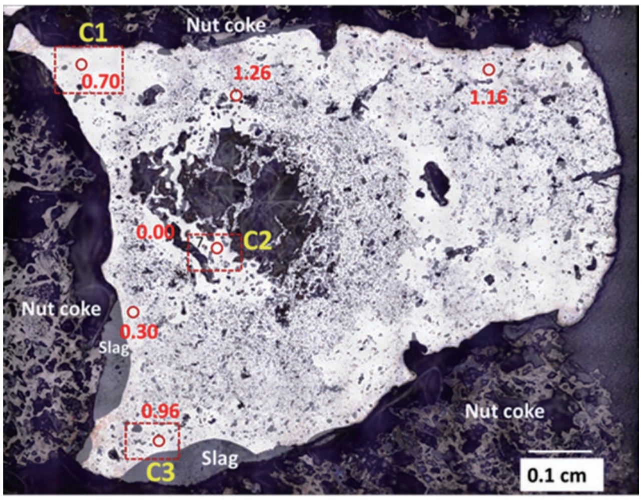


Fig. 10(a). Micrograph of the region C selected from the pellet bed mixed with (40 wt%) nut coke, quenched at 1 450°C (Fig. 9). (Online version in color.)

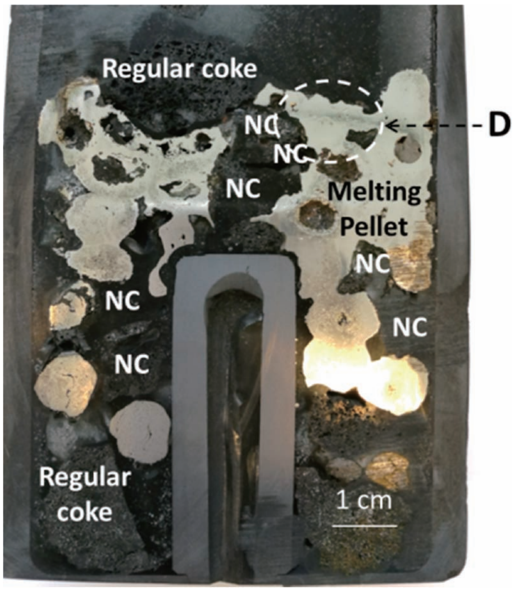
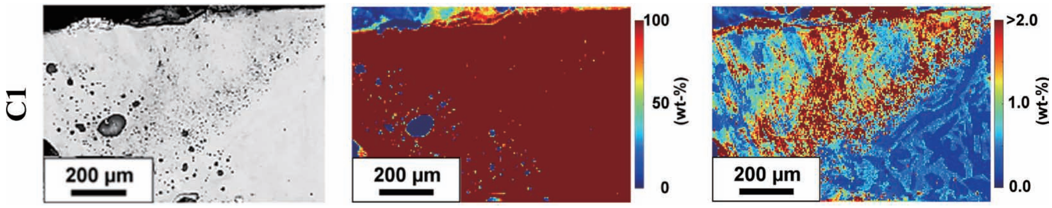
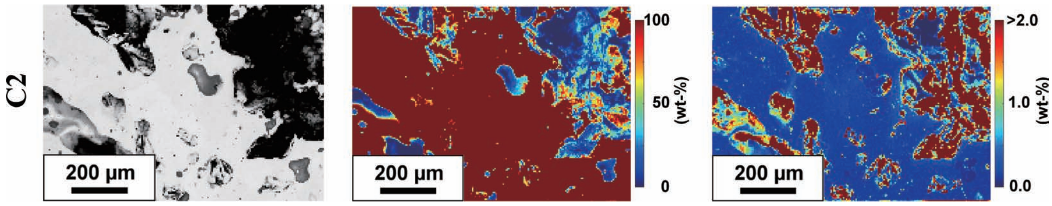


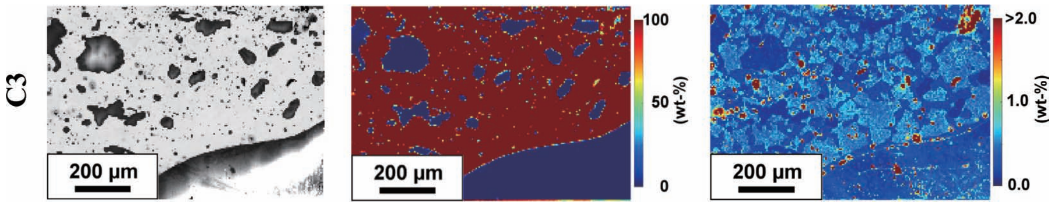
Fig. 11. Pellet bed mixed with 40 wt% nut coke, quenched at 1 500°C. (Online version in color.)



(a). Backscattered electron image
(b). Iron distribution (EPMA)
(c). Carbon distribution (EPMA)



(d). Backscattered electron image
(e). Iron distribution (EPMA)
(f). Carbon distribution (EPMA)



(g). Backscattered electron image
(h). Iron distribution (EPMA)
(i). Carbon distribution (EPMA)

Fig. 10(b). EPMA area scan at location C1, C2 and C3 from Fig. 10(a). (Online version in color.)

mation and provides pores for the gas flow. Additionally, due to the higher reduction degree realised on the iron ore pellets in the presence of nut coke, thicker iron shell will form around the pellets. This will take relatively long time to carburise and melt out of the bed. Consequently, the rate of bed contraction is decreased in the presence of nut coke.

In the quenched sample bed, it is observed that the pellet shape is deformed significantly due to melting. The solid metallic areas in the quenched bed are the re-solidified liquid iron melts (Fig. 11). The EPMA analysis is performed on such metallic locations to determine the level of iron carburisation (**Fig. 12**). The analysis reveals that the carbon is inconsistently (0.22–2.21 wt%) distributed in the melting sample. The segregated profile of the carbon rich dendrites or grains is apparent for the scanned areas (Fig. 12(b)). The average carbon concentration (~0.97 wt%) is higher than in the case of pellet bed quenched from 1 450°C (~0.73 wt%). This is due to the increase in temperature, which accelerates the kinetics of iron carburisation.[24)] Furthermore, when the liquid iron flows over the coke, the reaction rate enhances due to the direct contact between the coke and liquid iron.

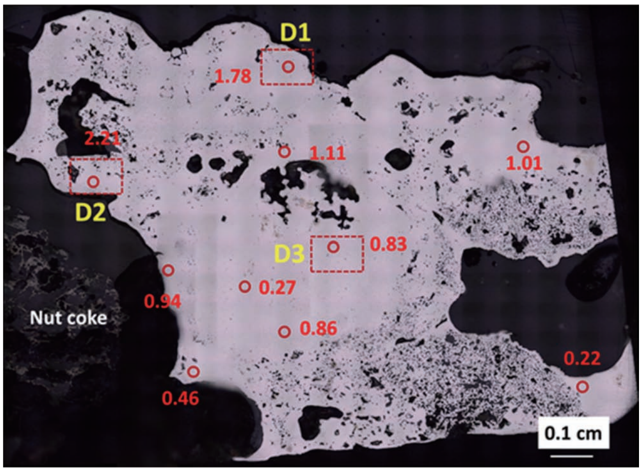
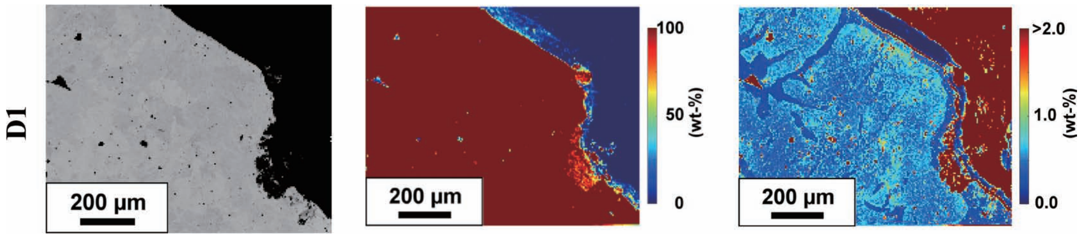


Fig. 12(a). (a) Micrograph of the region D selected from the pellet bed mixed with (40 wt%) nut coke, quenched at 1 500°C (Fig. 11). (Online version in color.)

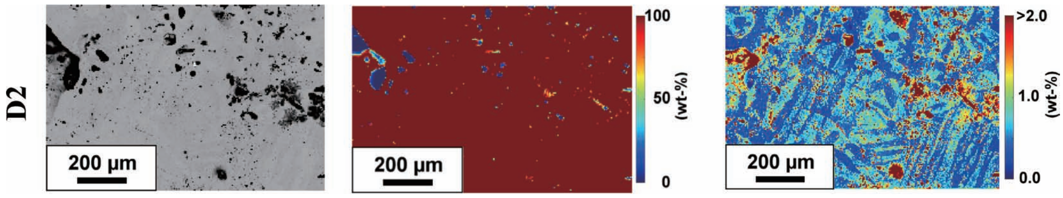
As the temperature increases during the experiment, based on the carburisation level achieved on the pellets, the melting begins. The melting starts from the location of the highest carbon content, provided that the carbon concentration is less than 4.3%[25)] in the pellet, which is at the point of contact between the coke and iron (shell). Consequently, the melting starts from there, then it spreads to the individual pellet. In the case of a pellet bed without nut coke, the melting occurs layer by layer. On the other hand, the presence of nut coke provides multiple sites for the iron carburisation. As a result, simultaneous melting occurs in the pellet bed mixed with nut coke. Furthermore, due to the higher level of iron carburisation, the bed melting temperature decreases with increasing nut coke addition in the pellet bed.[16)]

3.4. Effect of Nut Coke on Liquid Dripping

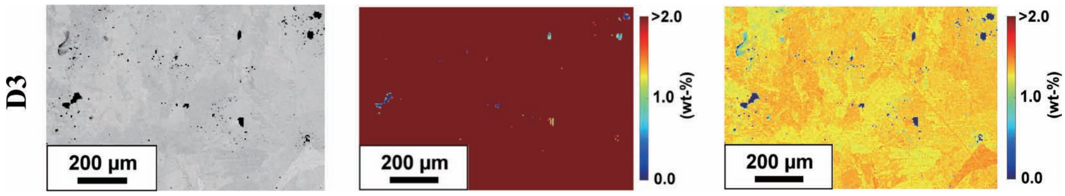
In the blast furnace, the liquid drips out from the cohesive zone and flows over the active coke zone to reach the hearth. While liquid is dripping out of the cohesive zone, many important reactions occur such as the direct reduction of FeO rich slag, liquid iron carburisation, sulphur and silicon transfer.[3)] Furthermore, the dripping pattern of the liquid is strongly linked to the gas intake capacity and therefore to the productivity of the blast furnace.[3)]



(a). Backscattered electron image
(b). Iron distribution (EPMA)
(c). Carbon distribution (EPMA)



(d). Backscattered electron image
(e). Iron distribution (EPMA)
(f). Carbon distribution (EPMA)



(g). Backscattered electron image
(h). Iron distribution (EPMA)
(i). Carbon distribution (EPMA)

Fig. 12(b). EPMA area scan at location D1, D2 and D3 from Fig. 12(a). (Online version in color.)

Since the nut coke is utilised as a replacement of the regular coke, it is expected that nut coke addition will have an impact on the liquid dripping pattern. On the one hand, nut coke use results in thinning of the regular coke layer, which might affect the residence time (reaction) of liquid. On the other hand, nut coke enhances the area of contact between the liquid and the coke to affect the reaction and dripping behaviour. Therefore, it is crucial to understand the nature of liquid dripping in the presence of nut coke in the iron ore pellet bed.

3.4.1. Dripping Temperature

The liquid drips out of the sample crucible and is collected at the cup located at the sample receiver (Fig. 2). The time and the temperature (T_{xf}) of the first liquid drop are marked after visualising the event from the glass window located at the receiver (Fig. 3). The liquid is observed to drip in the form of rivulets. However, a variation in dripping frequency is observed due to the stochastic nature[26] of the liquid dripping from the coke bed. The variation in liquid dripping is a result of the liquid (slag and metal) and solid interaction (coke). For example, the liquid iron turns from wetting (contact angle of 50° for 0% C) to non-wetting (130° for 5% C) with an increase in the carbon concentration.[27] The wetting nature of the liquid iron during melting and dripping in the pellet bed quenched from 1 500°C can be clearly seen in **Fig. 13**.

It is observed that the temperature of the first liquid drop (T_{xf}) is in the narrow range of 1 495-1 510°C (**Fig. 14**). On the other hand, the dripping temperature (T_d) derived from the pressure drop curve is observed to decrease with the nut coke addition in the pellet bed (Fig. 14). In the blast furnace, the temperature T_d is crucial because at this temperature the regime of high resistance to the gas flow ends by the pressure drop returning to the base value (P_{Base}). By this temperature, a significant number of voids are regained after the liquid flow through the bed.

The temperature difference between the dripping temperature (T_d) and actual first drop liquid dripping (T_{xf}) decreases with the nut coke addition in the pellet bed (Fig. 14). This represents the faster recovery of the voids for the gas flow, which principally occurs due to the simultaneous melting of the pellets in the presence of the nut coke in the bed.

3.4.2. Drip Liquid Chemistry

During the liquid flow over the coke, the reduction (of liquid FeO rich slag) and carburisation (of iron) takes place. For all melting experiments, the carbon concentration in dripped metal is observed in the range of 2.5 wt% to 3.5 wt% (**Fig. 15**(a)) and the FeO fraction in the slag is observed in range 3 wt% to 4 wt% (Fig. 15(b)). Considering the high carbon concentration in the pellet quenched in the presence of mixed nut coke (Figs. 10 and 12), it is expected for the dripped liquid to have higher carbon concentration in iron and low FeO fraction in the slag. However, no clear trend for the dripped metal and slag chemistry is observed. Additionally, a high variation in the metal-carbon content and slag FeO fraction is observed. This indicates the complex nature of the liquid dripping. Furthermore, the uncertain nature[17] of liquid dripping from the coke bed can possibly

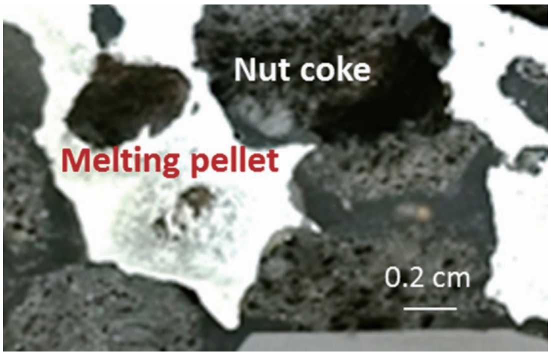


Fig. 13. Wetting nature of liquid iron, quenched at 1 500°C, with 40 wt% mixed nut coke. (Online version in color.)

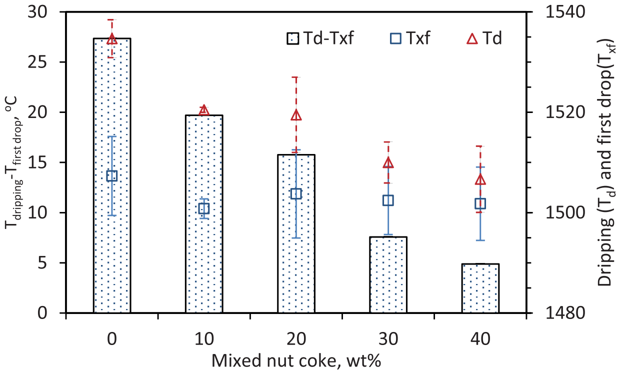
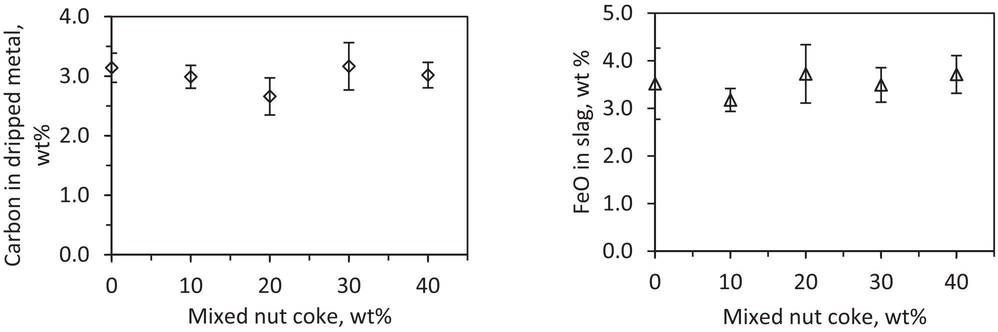


Fig. 14. Effect of nut coke addition on the dripping temperatures (T_d and T_{xf}). (Online version in color.)



(a) (b)

Fig. 15. Effect of nut coke mixing on (a). Carbon in the dripped metal, and (b). FeO in the slag.

result in variation in the reaction time for the liquid with the coke. Furthermore, the dripped history of the analysed sample is unknown, since the liquid from one melting experiment is collected in one cup.

Therefore, to understand the effect of nut coke addition on the dripped liquid mass and chemistry (carbon and FeO contents), experiments are performed in which the liquid is collected over the temperature range. The results are discussed in the following section.

3.4.3. Dripping Profile

Two control experiments are performed — first without nut coke and second with 40 wt% mixed nut coke in the pellet bed. The dripped liquid was collected in different cups to study the effect of dripping time and temperature on the liquid chemistry (metal and slag) and weight distribution (**Fig. 16**). The temperature range and the collected weight of the samples are given in **Table 4**.

It is noticed from both the experiments (with and without nut coke) that first, only molten metal drips out of the bed, which indicates that the melting and dripping phenomena are controlled by the melting of the metal (iron). Thereafter, metal and slag simultaneously drip out of the bed. Dripping from the sample bed mixed with nut coke starts at a lower temperature (1 500°C) compared to the case when nut coke is absent (1 518°C). It is observed for both experiments that the liquid drips in the form of rivulets. The dripping frequency is seen to vary in a close weight range (~7 g/°C) for the pellet bed mixed with nut coke, whereas, for the pellet bed without nut coke, a significant fraction of liquid drips (~50 wt%) at higher temperature (~1 550°C). This delay in liquid dripping from the pellet bed without nut coke, indicates that the iron is lean in carbon at the start of melting.[25] Then, as the temperature increases, the liquefaction occurs in the bed to continue the dripping.

(1) Iron Carburisation

The carbon present in the dripped iron melt is shown in **Fig. 17**. The average carbon content of the dripped metal from the pellet bed without nut coke is higher (3.40 wt%) compared to the case when nut coke (40 wt%) is present (2.75 wt%) in the bed. Considering higher solid-state carburisation (Fig. 10) in the pellet bed mixed with the nut coke, this is contrary to the expectation. There are two possible reasons for such behaviour in the pellet bed without nut coke. First, the dripping at high temperature supports the kinetics of the iron carburisation in the liquid state. Second, when the liquid iron flows through the thicker regular coke layer at high temperature, it possibly accumulates more carbon from the coke.

In the case of a pellet bed without mixed nut coke, the carbon content in the iron is observed to increase with temperature up to 1 533°C. Then, it is observed similar for the

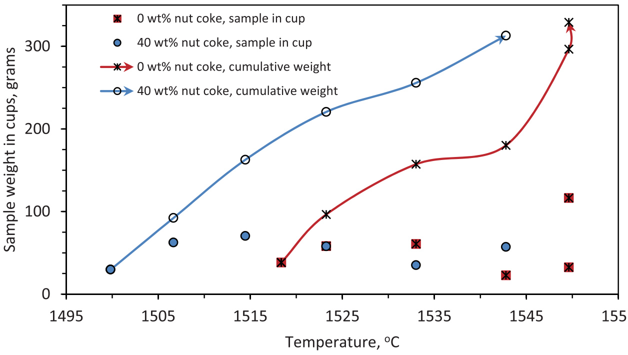


Fig. 16. Distribution of the dripped liquid weight collected over the temperature range. (Online version in color.)

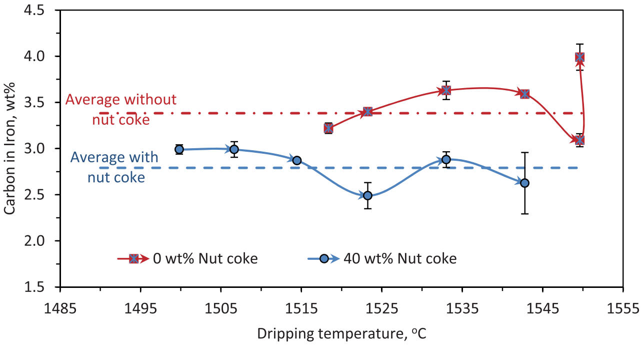


Fig. 17. Carbon composition of the dripped iron metal. (Online version in color.)

Table 4. Sample weight after the dripping experiments.

Experiment	Cup number	Temperature range,°C		Weight, grams		Material, Metal and/or slag	Remark
		From	To	Liquid weight	Cumulative		
Without nut coke	1	1 518	1 523	38.4	38.4	Metal	–
	2	1 523	1 533	58.2	96.6	Metal and Slag	–
	3	1 533	1 543	60.8	157.3	Metal and Slag	–
	4	1 543	1 550	22.8	180.2	Metal and Slag	–
	5	1 550	1 550	116.4	296.6	Metal and Slag	Hold for 5 min
	6	1 549,6	20,0	32.5	329.0	Metal and Slag	During cooling cycle
With 40 wt% nut coke	1	1 500	1 507	29.8	29.8	Metal	–
	2	1 507	1 515	62.6	92.3	Metal and Slag	–
	3	1 515	1 523	70.4	162.8	Metal and Slag	–
	4	1 523	1 533	57.9	220.7	Metal and Slag	–
	5	1 533	1 543	35.1	255.8	Metal and Slag	–
	6	1 543	1 550	57.2	312.9	Metal and Slag	–

collected metal up to 1 542°C. Thereafter, the carbon content is decreased by 0.5 wt% which is due to the large volume of liquid dripped around this temperature (Fig. 16). As a result, the liquid does not get sufficient time to carburise by the regular coke. After that, some liquid drips out of the crucible at the start of the cooling cycle. This liquid is able to drip out due to its high carbon content which decreases the liquidus temperature and lowers the viscosity by providing the available superheat.

On the contrary, in the pellet bed mixed with nut coke, the carbon content in the dripped iron is observed to be in a close composition range (2.50–3.00 wt%). However, a mild fluctuation in the carbon concentration is observed in samples collected at high temperature (1 515°C to 1 523°C), this might be a result of hold-up and stochastic dripping nature.[26] As the temperature increases, more iron-carbon alloy will liquefy which will flow through a thinner layer of regular coke compared to the bed without nut coke. As a result, liquid iron has less time to interact with the regular coke to accumulate the carbon. Nevertheless, the carbon concentration in the dripped liquid is in a close range (~2.75 wt%). This is possibly due to the steady dripping of the liquid from the bed when nut coke is present.

(2) FeO in the Dripped Slag

The average FeO content in the dripped slag for the nut coke mixed case is observed to be low (3.8 wt%) compared to the case in which the nut coke is absent (4.6 wt%) in the pellet bed (**Fig. 18**). The lower level of FeO in dripped slag indirectly indicates that a higher reduction degree is achieved in the case of pellet mixed with nut coke.

For both cases, the dripped slag reaches a final FeO level of ~3.1 wt% (**Table 5**). In the case of pellets mixed with nut coke, this FeO level is achieved at a lower temperature than in case of pellet without nut coke. In the case of pellet mixed with nut coke, after some initial variation, the FeO concentration eventually reaches the final level (3.1 wt%) whereas, in the case of pellet bed without nut coke, slag that drips at a high temperature (above 1 542°C) and has the stable level of FeO. This final FeO content in slag might be the result of stable oxide complex formation with other oxides (CaO, SiO_2, Al_2O_3, MgO), which need longer interaction time with coke for further reduction. The complete slag analysis is given in Table 5.

3.5. Coke Consumption

The coke utilised during the experiments is given in **Fig. 19**. In general, the variance in the nut coke utilisation is high, the irregular shape (variance in surface area) of the nut coke can possibly bring these changes. Furthermore, the stochastic nature[26] of the liquid dripping from the bed will vary the reaction time of liquid iron and slag (FeO rich slag) to affect the coke utilisation.

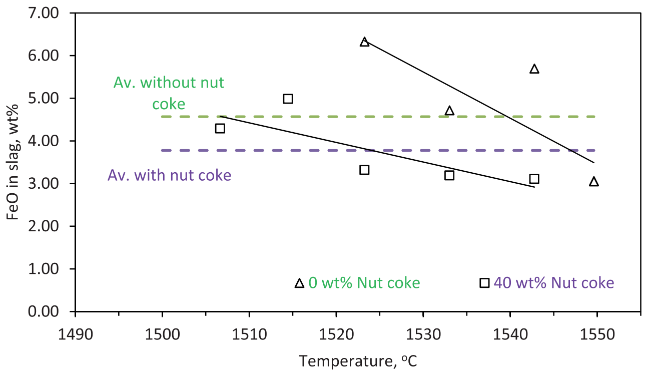


Fig. 18. FeO in the dripped slag. (Online version in color.)

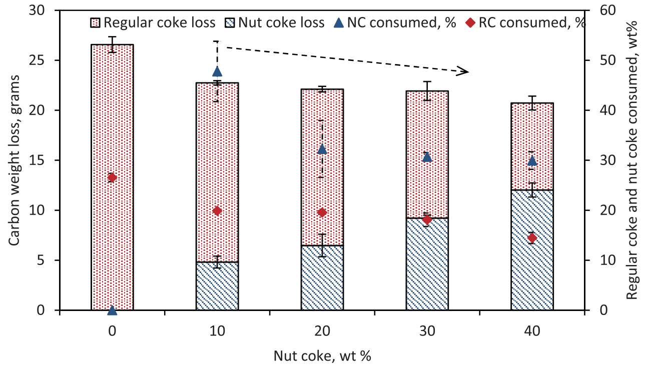


Fig. 19. Coke utilisation in the melting and dripping experiments. (Online version in color.)

Table 5. The dripped liquid slag chemistry.

Temperature, °C		Cup	SiO_2	FeO	MgO	Al_2O_3	MnO	CaO	TiO_2	V_2O_5	K_2O
Start	End		wt%								
Sample without nut coke											
1 523	1 533	2	47.4	6.3	13.2	14.5	4.7	5.5	4.7	0.3	1.0
1 533	1 543	3	47.7	4.7	12.9	17.3	4.2	5.2	4.5	0.3	1.1
1 550	1 550	4	43.9	5.7	12.5	15.2	6.4	6.0	5.8	0.3	1.2
1 550	1 550	5	49.6	3.1	13.2	17.2	3.9	5.3	4.5	0.2	1.1
1 550	–	6	49.8	3.1	13.2	15.9	4.0	5.6	4.8	0.1	1.1
Sample with 40 wt% mixed nut coke											
1 507	1 515	2	49.3	4.3	13.9	13.7	4.4	5.8	4.9	0.3	1.1
1 515	1 523	3	47.6	5.0	12.6	17.0	4.3	5.2	4.5	0.3	1.3
1 523	1 533	4	50.1	3.3	14.0	14.0	4.3	5.9	4.9	0.2	1.2
1 533	1 543	5	50.6	3.2	13.7	14.7	3.9	5.8	4.7	0.1	1.1
1 543	1 550	6	49.5	3.1	14.2	14.9	3.7	6.0	5.0	0.1	1.2

The total coke utilisation is also observed to decrease with the nut coke addition in the pellet bed. First, a drastic drop in total coke utilisation is noted with 10 wt% nut coke addition in the pellet bed. Then a gradual decrease in the weight of the total consumed coke is noticed. Nevertheless, the nut coke is observed to be utilised in place of the regular coke (Fig. 19). Additionally, the fraction of the regular coke consumed is seen to decrease with the nut coke mixing in the pellet bed. This indicates that the nut coke is preferentially utilised to fulfil the chemical functions (reductant and iron carburiser) of the coke in the blast furnace conditions. Furthermore, less utilised regular coke will be of a bigger size, which will reach the blast furnace hearth to support the liquid permeability.

4. Conclusions

By performing a series of experiments under simulated blast furnace conditions, the following conclusions can be drawn.

(1) In the melting bed of iron ore pellets, nut coke is present as a skeleton to maintain the passage for the gas flow.

(2) By direct contact with the coke, the formed iron shell of the pellets becomes carburised first then melts eventually. In case of pellet bed without nut coke, this starts from the first top layer and progresses layer-wise. On the other hand, in the pellet bed mixed with nut coke, melting proceeds simultaneously due to the presence of multiple points of contact between the coke (nut coke and regular coke) and pellets across the whole bed.

(3) The higher iron carburisation achieved in the presence of the nut coke is observed to be the prime reason for the decrease in the melting point of the pellet bed.

(4) The difference between the first liquid drop temperature (T_{xf}) and the derived dripping temperature (T_d) is observed to decrease with the nut coke mixing in the pellet bed.

(5) In the case of pellet mixed with nut coke (40 wt%), the liquid dripping starts earlier at lower temperature (1 500°C) than the case when nut coke is absent (1 518°C). In the nut coke mixed pellet bed a steady rate of liquid dripping occurs, whereas from the pellet bed without nut coke a significant amount of liquid drops (~50 wt%) at higher temperature (above 1 542°C).

(6) A substantial degree of iron carburisation occurs in the liquid state, which is indicated by the difference in the carbon level of quenched pellet and the dripped metal.

In the case of sample bed without nut coke, a higher carburisation occurs when liquid iron flows through the thicker regular coke layer. In the pellet bed mixed with nut coke the liquid state carburisation is observed to be low due to the presence of the thinner regular coke layer.

(7) The nut coke is consumed in preference to the regular coke. Additionally, the total coke consumption is noticed to decrease with the nut coke mixing in the pellet bed.

Acknowledgement

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