Sinter strength evaluation using process parameters under different conditions in iron ore sintering process

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Abstract

There exists internal connection between the process parameters and real sinter quality in the sintering process. However, few investigations on bridging the process parameters and real sinter quality for engineering applications were reported. For example, only process parameters (flow resistance, heat condition of sintering bed and off-gas composition) can be obtained by numerical method in the previous studies. Actual sinter strength and reducibility can't be captured due to lacking of reliable models and the limited computing resource. This paper focused on solving the problem, which was substantial for parameters optimizing in both numerical simulation and on-line control of sinter quality. The melt quantity index (*MQI*), combining the peak temperature and duration time of melting temperature (*DTMT*), was used in this study. We also explained its physical significance as the effective “energy” for melting phase formation. Then the corresponding relation between *MQI* and sinter yield was widely confirmed by our own experimental data and the reproduced data from published references. Consequently, the *MQI* was recommended as a wise indicator of real sinter strength. The effects of three operating parameters (fixed carbon content, sintering pressure and fuel reactivity) on sinter strength were investigated by examining the *MQI*, sintering speed and air flowrate. Besides, the influencing mechanism of two important performance parameters (combustion and heat utilization efficiencies) on *MQI* was clarified. The monitoring of the above parameters would provide a powerful support for the transparency of sintering process “black-box” and optimization of operating parameters. Finally, a conceptual design for the on-line control of sinter strength was even proposed based on the present results.

Key words: melt quantity index; sinter strength indicator; operating parameters; performance parameters; on-line control; iron ore sintering

Nomenclature

c	Specific heat capacity in constant pressure, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
T	Temperature, $^{\circ}\text{C}$
v	Gas velocity, $\text{m}\cdot\text{s}^{-1}$
y	Coordinate direction, mm
W	Work, J
f_0	Friction force, N
F	Pulling force, N
P	Position of object
s	Displacement, m
$DTMT$	Duration time of melting temperature, s
FFS	Flame front speed, $\text{m}\cdot\text{s}^{-1}$
MQI	Melt quantity index, $^{\circ}\text{C}\cdot\text{s}$
$HTFS$	Heat transfer front speed, $\text{m}\cdot\text{s}^{-1}$

Greek symbols

τ	Time, s
ε	Porosity
ρ	Density, $\text{kg}\cdot\text{m}^{-3}$
η	Heat utilization efficiency

Subscripts

p	Peak
m	Melting
g	Gas
s	Solid

1. Introduction

The integrated iron & steel industry is the most energy-intensive sector, accounting for 10-15% of the total energy consumption in the world [1]. In 2009, the CO₂ emission from Chinese iron and steel sector is nearly equal to 50% of the world's steel industry's CO₂ emission [2]. It is aimed at converting iron ore fines to suitable feed for efficient iron-making in the blast furnace using agglomeration technology. The process is complex and involves various physical and chemical phenomena such as momentum, heat and mass transfer coupled with combustion, melting, solidification, evaporation and condensation. Within the descending narrow flame front, the melting and coalescence of iron ore fines occur. After cooling and solidification, sinter cakes with better gas permeability are obtained. Lu [3] described the detailed process of sintering. Producing sinters of suitable quality at the lowest fuel rate and the highest productivity is the ultimate goal of most operations. Therefore, various fundamental researches and new technologies have been investigated by numerical and experimental methods in the last decade.

Yang [4] verified their numerical model and examined the effects of coke content, air supply and fuel type on peak temperature, melting zone thickness and flame front speed. Zhou [5] improved the previous model by considering detailed reactions, melting and solidification sub-models. Then sensitivity analyses results [6] showed that the bed bulk density, solid and gas thermal capacities, coke level and size and post-ignition air flowrate had large influences on flame front speed and heat pattern. And in their subsequent work [7], the computational model was further improved by integrating the granulation impact and two endothermic reactions into the heat treatment model. Zhou [8] numerically investigated the feasibility of utilizing spent ion exchange resin (SIER) in iron ore sintering process. The authors established a 3-D model to examine the thermal conditions at different mass fractions of spent ion exchange resin (SIER). Nath [9] carried out the mathematical modelling and optimization of two-layered sintering process for sinter quality and fuel efficiency using genetic algorithm. Pahlevaninezhad [10] numerically investigated the sintering process by comprehensively considering the chemical reactions in gas and solid phase. A wide range of parameters, including coke and limestone size, inlet air velocity and coke content were carefully examined. Mitterlehner [11] developed a simulation model of the sintering process with special focus on the propagation velocity of the heat front through the bed.

The effects of program-internal and user provided parameters were evaluated using this model. Ahn [12] proposed a modelling approach for a sintering bed using flowsheet process simulator as the starting point for studying the effect of flue gas recirculation on the sintering process. In the companion paper [13], the details of the modelling cases and the corresponding results were reported. The above simulation investigations adopted porous medium model, ignoring the single particle behaviour and different particles interaction. The detailed processes of melting and coalescence were also neglected due to the limited computing resource and inaccurate mathematical model. As a consequence, the sinter strength can't be captured in the simulation. At the current stage, simulation method can only model the heat transfer, mass transfer and combustion phenomena as an auxiliary means of experimental test. If a reliable and convenient method bridging the process parameters (such as thermal and combustion performances) and real sinter quality indices is developed, simulation work would play a much more important and extensive role on optimizing the operating parameters and predicting the performance at extreme conditions. However, a small amount of work on solving the problem has been reported.

There is another typical problem bothering the operators for a long time. When the sintering process progressed, the solid fuel burning and water evaporation increase the porosity and improve the oxygen supply and bed permeability. Moreover, the increasing preheating time improves the combustion and heat utilization efficiencies. In the conventional case, the above changes will lead to an imbalance of heat distribution which is inevitable, as shown in **Fig. 1(a)**. For example, insufficient heat in upper bed results in low sinter strength and excessive heat in lower bed leads to the energy waste. In the ideal case, heat distribution should be optimized to produce uniform sinters, as shown in **Fig. 1(b)**. Segregation of solid fuels and charging condition were investigated with the aim at improving the heat distribution in sintering bed [14]. Zhou [15] proposed a novel technique, three-layered bed structure, to study the effect of coke level, properties and combustion behaviour on NO_x emission. In order to maximize the combustion efficiency and optimize the heat distribution, the effect of additional oxygen supply with an adjustment of injection position was discussed [16]. The gaseous fuel injection technology was developed [17], which provided a secondary combustion area above the original combustion area to produce high quality sinter without increasing the fuel consumption. Castro [18] carried out the numerical investigation on gaseous fuel injection technology. On this basis, Iwami [19] employed

the oxygen enrichment method with an aim at controlling the position of secondary combustion area. Adding fuel externally to the raw ores was adopted and found to be beneficial to fuel combustion in both lab-scale sintering pot [20] and commercial sintering plant [21]. Loo [22] developed a laboratory sintering technique. Then based on the new technique, the effects of bed height, limestone, the level of return fines, mix moisture and suction on sintering behaviour were examined [23]. Zhou [24] studied the influence of flame front on sintering production and quality. Abreu [25] adopted charcoal as supplementary fuel in the iron ore sintering process. The results indicated that the blend with 50% charcoal in the fuel mix was possible from both environmental and operational perspectives. However, the inaccuracy and hysteresis of manual adjustment of fuel segregation, fuel particles size, fuel distribution and even external operation are not able to satisfy the future automatic management of sinter production. Actually, on-line control is a perfect alternative method to solve this problem. It is noted that, reliable and quick sintering performance indicators are required because we need feedbacks to adjust operating parameters accordingly in time. The real-time visualisation of sintering process “black-box” is a powerful support to the on-line controller. Thus, the connection of process parameters and real sinter quality indices is in an urgent need for the on-line control process. However, few researchers paid attention to this for engineering applications. Fortunately, limited fundamental investigations on melting and bonding mechanisms in the iron ore sintering process provided a theoretical support for the work. For example, Wu [26] carried out experimental study of assimilation characteristics of 12 kinds of iron ores which were very important to the fluidity of liquid phase and bonding strength of sinter body.

Based on the above survey, reliable and quick connection of the process parameters and real sinter quality indices is very helpful for the simulation results analysis and the on-line control. In this paper, we would try to find the connection based on the data from our experiments and previous studies. According to the authors’ knowledge, almost no such investigations were performed previously.

2. Experimental method and parameters quantification

The commercial tests in sintering grate are enormously expensive. If the transfer phenomena in the directions of grate length and width are neglected, iron ore sintering can be considered as

1-D (in the direction of bed height) unsteady process. The time axis can be transformed into length by multiplying the traveling speed [4]. For this reason, the commercial tests can be performed in a fixed reactor in laboratory scale known as “sintering pot” tests which are extensively adopted in this field [24]. The sintering process was simulated in a fixed reactor with a height of 400 mm and a diameter of 142 mm. Experimental system and materials used in the present study can be found from our previous published work [27]. Three sets of experimental tests were arranged, as shown in **Table 1**. All the materials were carefully mixed and granulated by adding water to achieve the same moisture content in the granulation drum for 5 min. For every test, 350 g hearth ore and approximate 10 kg raw mix after granulation were fed into the sintering reactor. It was difficult to control the post-ignition air flowrate accurately, because temperature distribution and air flowrate were coupled. In the present study, the air flowrate was approximately controlled by varying sintering pressure, keeping cold permeability unchanged. The control accuracy of sintering pressure was $\pm 0.4\%$.

For certain raw mixtures, sintered ores strength is highly related to the thermal condition and combustion performance in sintering bed. The duration time of melting temperature (*DTMT*), flame front speed (*FFS*) and sinter yield have been defined in our previous published work [27]. Actually, yield is a kind of sinter strength index, as well as the shatter index and tumble index. Particularly, some important parameters are defined below.

- (1) Melt quantity index (*MQI*) is defined as the enclosed area above 1100 °C (initiating temperature of melting process [24]) in temperature-time profile, as shown in **Fig. 2**. *MQI* can be obtained by integrating **Eq. (1)**.

$$MQI = \int_{\tau_1}^{\tau_2} (T - 1100) \cdot d\tau \quad (1)$$

where τ_1 and τ_2 are the beginning time and ending time of melting process.

- (2) Heat transfer front speed (*HTFS*) is the travelling speed of heat transfer front, which can be estimated by **Eq. (2)** [27].

$$HTFS = \rho_g v_g c_g / [\varepsilon \rho_g c_g + (1 - \varepsilon) \rho_s c_s] \quad (2)$$

- (3) According to the theory reported in [28], it is helpful for energy accumulation in high temperature zone when the speeds of heat transfer front and flame front are close. Consequently, we introduce a new parameter to evaluate the heat utilization efficiency, as

expressed in **Eq. (3)**.

$$\eta=1-|HTFS - FFS| / HTFS \quad (3)$$

3. Results

3.1 Reference case analysis

The reference case (Case 1) in **Table 1** represented an operating condition where the fixed carbon content was 3.48%; ignition and sintering pressures were 5 kPa and 10 kPa. Typical temperature-time profiles of sintering bed are shown in **Fig. 3**. In the case of thermocouple 1 (TC 1), a nearly constant temperature around 60-70 °C indicated the water evaporation was occurring at the beginning. After that, hot gas preheated the reactive pellets. The coke combustion commenced when the temperature reached its ignition point. Then the local temperature rose to the peak value quickly which suggested combustion process finished. Finally, the bed temperature fell down due to the convective cooling of fresh air. The flow and coalescence of melting phase provide the bonding force for the separated particles. The amount and rate of melt formation are highly dependent on the heat pattern in melting zone. Time interval between the adjacent points in a temperature-time profile is about 1 s. Therefore, we have enough samples to draw the isotherms in melting zone. For each position in the height direction, we can obtain the corresponding time of 1100 °C, 1150 °C, 1200 °C and 1250 °C in both temperature rising and dropping periods by linear interpolation, as show in Fig 4(a). **Figure 4(a)** shows the isotherms above 1100 °C in melting zone. It was obvious that the melting zone thickness in upper bed was much thinner than that in lower bed. The typical heat distribution pattern agreed well with the sinter strength indices in different layers of sintering bed. To describe the heat pattern in melting zone more intuitively, a reconstructed temperature contour of melting zone is shown in **Fig. 4(b)**. Figure 4(b) was plotted using the “color fill” function in Origin 9.0 based on the above isotherm data.

Previous researchers adopted the peak temperature or *DTMT* to characterize the heat pattern of melting zone. In the present study, the *MQI* integrating the above two parameters was preferred. The *MQI* was more reasonable and comprehensive to accurately reflect sinter strength for engineering applications (simulation results analysis and sinter strength on-line control). Imagining that an object was pulled from position 1 to position 2, as shown in **Fig. 5(a)**, the

effective work acting on the object can be calculated by **Eq. (4)**. Since extra energy had to be paid for overcoming the friction (f_0), the effective work was just the enclosed area in **Fig. 5(b)**. Similarly, MQI can be regarded as the effective “energy” for the melting phase formation in sintering bed. In other words, extra “energy” also had to be paid for the activation of melting process.

$$W = \int_{P_1}^{P_2} (F - f_0) \cdot ds \quad (4)$$

where P_1 is the initial position and P_2 is the final position of the moving object.

The relation between sinter yield and average MQI of three tests, as well as peak temperature and $DTMT$, was plotted in **Fig. 6(a)**. In the present study, Case 1 was repeated three times at the same condition. The local MQI , peak temperature and $DTMT$ in Fig. 6(a) were the average values of the three tests. The local sinter yields were tested after dividing the sinter cake into four parts: 0-100 mm, 100-200 mm, 200-300 mm and 300-400 mm. It was noted that, the peak temperature and $DTMT$ agreed well with local sinter yield in general. However, the local peak temperature and $DTMT$ appeared some fluctuations due to the random distribution of solid fuels in sintering bed which was inevitable. Compared with peak temperature and $DTMT$, the MQI including comprehensive information was much more robust and closer to local sinter yield. Consequently, MQI seemed to be a perfect indicator to sinter strength with a clear physical significance. To further valid the relation between sinter strength and MQI , data from a wide range of published references were reproduced and compared. The MQI and strength indices (such as yield, shatter strength, tumble strength and tensile strength) were plotted in a same map, as shown in **Fig. 6(b)**. We can see that, MQI can always reflect the trend of sinter strength for a certain set of tests. Therefore, MQI is recommended as an indicator to connect the process parameters and sinter strength.

3.2 Parametric studies

In this section, we examined the effects of three operating parameters: fixed carbon content, sintering pressure and fuel category on sinter strength (MQI). Moreover, two performance parameters: combustion and heat utilization efficiencies were also included in our investigation.

3.2.1 Effect of fixed carbon content

The fixed carbon content plays a dominate role for the melting process. In fact, the burning

solid fuels provide high temperature environment for melting phase formation in the sintering bed. Therefore, we examined the effect of fixed carbon content on local *MQI* for Case 1, Case 2 and Case 3, as presented in **Fig. 7(a)**. It was found that the local *MQI* increased with the rise of fixed carbon content from 3.26% to 3.70%. From a view of energy balance, the rise of local *MQI* with the increasing fixed carbon content was quite easy to accept. However, the increment of *MQI* was very limited when the fixed carbon content increased from 3.48% to 3.70%. The variation of O₂ supply may provide some clues to explain the phenomena. When raising the fixed carbon content at a low level, there was still enough O₂ to react with CO in the high speed bulk gas. However, further increasing the fixed carbon content, oxidation process in sintering bed became a typical oxygen-limited reaction, thereby the energy conversion efficiency reduced at the limited O₂ supply and high fixed carbon content. The waste gas composition indicated that CO concentration increased significantly at high fixed carbon content [4]. Therefore, simply increasing the fixed carbon content may not always work efficiently at an unchanged O₂ supply. Other than sinter strength, sintering time was another critical parameter which determined the productivity of sintered ores. The obtained sintering time at different fixed carbon content are listed in **Table 2**. The results suggested that the sintering time was not very sensitive to fixed carbon content. Only a slight reduce of sintering time was observed as the decrease of fixed carbon content. This was attributed to the higher temperature and thicker melting zone thickness, resulting in a decreased air flowrate, as shown in **Fig. 7(b)**.

Figure 7(c) shows the relation between *MQI* and sinter yield at different fixed carbon content. Generally, the corresponding relation of *MQI* and sinter yield was confirmed again within a range of fixed carbon content. If the fixed carbon content was too low, the *MQI* reduced significantly, leading to low sinter strength. On the other hand, if the fixed carbon content was too high, the excessively high *MQI* resulted in low porosity of sinter products, attributing to higher energy consumption in the next step of iron making. Therefore, controlling *MQI* may be an effective option to produce high strength sinter and uniform sinter at an optimum fixed carbon content.

3.2.2 Effect of sintering pressure

In this part, three tests were conducted at the sintering pressures of 10 kPa, 12 kPa and 14 kPa, while other operating parameters remained unchanged. **Figure 8(a)** shows that increasing the sintering pressure would cause considerable decline of the local *MQI* for Case 4, Case 5 and Case

6. Consideration of the increased air flowrate and O_2 supply may find some clues of interpretation. The increased sintering pressure not only accelerated the descending flame front but also enhanced the cooling rate of hot sinters which adversely affected the energy accumulation in melting zone. In the previous work of Pironi [32] and Pahlevaninezhad [10], similar trends were found in smouldering combustion of non-aqueous phase liquids (NPAL) and sintering process. On the other hand, for fixed amount of fixed carbon content in the sintering bed, higher combustion rate was obtained in the case of more O_2 supply. As indicated in **Table 2**, the results suggested that the sintering time was quite sensitive to sintering pressure. Higher sintering pressure resulted in higher sintering speed due to the increased air flowrate, as shown in **Fig. 8(b)**. In the beginning, the air flowrate of 12 kPa followed closely the air flowrate of 14 kPa at relatively high flow resistance. Then the air flowrate sharply increased due to the rapid emission of the trapped water in the lower part of sintering bed, so that the air “flowrate gap” between 14 kPa and 12 kPa was extended in this period. Moreover, the fluctuation of air flowrate-time profile was inevitable and also found in other research [4]. Unfortunately, the wave peak of 12 kPa and the wave trough of 14 kPa were encountered near 600 s, which resulted in the very close air flowrate between 14 kPa and 12 kPa.

Figure 8(c) depicts the relation between MQI and sinter yield at different sintering pressures. Within the studied range of sintering pressures, for higher MQI , the higher yield (sinter strength) was obtained as expected. The corresponding relation of the two parameters was confirmed again. It was noted that, if the sintering pressure was too high, the sinter strength can’t be ensured. On the other hand, the low sintering speed would reduce sinter productivity due to the low sintering pressure. Therefore, in the actual operations, the optimum sintering pressure should be determined by balancing the sinter strength (MQI) and productivity. For example, we can optimize the sintering speed under fixed sinter strength (MQI) by simulation approach.

3.2.3 Effect of fuel reactivity

Coke breeze has been widely used as an ideal fuel for iron ore sintering process, but recent attempts to partially replace coke with less expensive or lower emissions fuels are effective in the actual operations. In sintering plant, solid fuels such as coke breeze, anthracite or even biomass are usually from different producing areas. Their reactivity differs from each other. Since low reactivity of anthracite had significant influence on sintering process [4], so we examined the

effect of fuel reactivity on *MQI* and sintering speed in this section. With the help of thermogravimetric analysis, lower combustion temperature range and higher weight loss rate of charcoal were obtained, which meant charcoal burned much earlier and faster than coke breeze. In other words, charcoal had a higher reactivity than coke breeze. In order to simulate the different fuel reactivity, we mixed the coke breeze and charcoal at different blending ratios for Case 7, Case 8 and Case 9, as shown in **Table 1**. To obtain more reliable results, we screened the solid fuels (coke and charcoal) into five parts based on their sizes: 0-1 mm, 1-2 mm, 2-3 mm, 3-4 mm and 4-5 mm using sieves with circular holes. For each test, we prepared the fuels according to Table 3 to make sure the similar bed structures.

Figure 9(a) shows the *MQI* evolutions at different fuel reactivity. It was observed that, increasing fuel reactivity would greatly influence the *MQI* even at the same fixed carbon content and sintering pressure. When the reactivity was excessively high (Case 9: 80% charcoal), the *MQI* decreased significantly. This was mainly caused by the poorly organized combustion at excessively high fuel reactivity. Moreover, as indicated in **Table 2**, the results suggested that the sintering time sharply decreased as the rise of fuel reactivity, resulting in a higher speed of descending flame front. This was another contributor of the decreased *MQI* at high fuel reactivity. The optimum blending ratio of different fuels should be determined by both *MQI* and sintering speed. Figure 9(b) shows the air flowrates at different fuel reactivity. Due to the sharply decreased *MQI*, post-ignition bed permeability of Case 7 was better than those of Case 8 and Case 9. Consequently, air flowrate of Case 7 was much higher, as shown in Fig. 9(b). Moreover, the relation between *MQI* and sinter yield is shown in **Fig. 9(c)**. The corresponding relation between *MQI* and yield was confirmed again at different fuel reactivity.

Except for operating parameters, the performance parameters (such as combustion and heat utilization efficiencies) also play key roles on the sinter strength. Actually, the comprehensive monitoring in on-line control system can provide a powerful support for “expert system” to knowledge the on-going sintering process. Clarifying the influencing mechanism of the two parameters is important for the “expert system” to give wise advices accordingly. In the following paragraphs, the effects of combustion and heat utilization efficiencies were analyzed.

3.2.4 Effect of combustion efficiency

Combustion efficiency determines the amount of heat converted from chemical energy at

certain fixed carbon content in the sintering process. In fact, accurately monitoring the local combustion efficiency in sintering bed was almost impossible. But for engineering applications, the waste gas composition at the outlet of sintering bed provided an available window for acknowledging combustion efficiency. There was an agreement that at the temperature above 727 °C, CO is the main product formed at the coke-gas interface [33]. In the typical temperature-time profiles shown in **Fig. 3**, local temperature rose rapidly from ambient temperature to 727 °C. Consequently, the main reactions can be approximately described by **Eq. (5a)** and **Eq. (5b)**. At the solid fuel surface, carbon material was oxidized to CO. Then the formed CO was further oxidized to CO₂ in the bulk gas.

Ooi [29] and Lu [34] adopted the ratio of CO₂ concentration ([CO₂]) and (CO₂+CO) concentration ([CO₂+CO]) as the indicator of combustion efficiency. In the ideal case, the [CO₂+CO] should be equal to 1.0 which meant the complete conversion of chemical energy to heat. **Figure 10(a)** shows the relation between *MQI* and combustion efficiency ([CO₂]/[CO+CO₂]) at the same fuel mass fraction. The results showed that for higher combustion efficiency, high sinter strength (*MQI*) was easier to be maintained.

According to **Eq. 5(b)**, O₂ concentration ([O₂]) in bulk gas was the key factor for CO oxidization process. Actually, the [O₂] near the burning fuel particles determined the conversion efficiency of CO to CO₂. Consequently, [O₂] was another indicator of combustion efficiency. Compared with [CO₂]/[CO+CO₂], monitoring the [O₂] was more convenient and cheaper. Beyond that, the monitored parameter and the controlled parameter were the same one. **Figure 10(b)** presents the relation between *MQI* and [O₂] at the same fixed carbon and sintering pressure. In Fig. 10(b), different points represent different sintering cases. *MQI* was the average value of local *MQI* recorded by the thermocouples in each position. Oxygen concentration was the time-average value of concentration-time profile measured by the gas analyser. The start of calculated time period was the corresponding time of the fuel ignition temperature at the first thermocouple position (top). The end of calculated time period was the corresponding time of maximum bed temperature at the last thermocouple position (bottom). What had to be pointed out was that the gas analyser and

temperature acquisition system were initiated at the same time. The results suggested that the MQI was also highly dependent on $[O_2]$ during the sintering process. For higher combustion efficiency, more generated heat was applied to the melting process, resulting in the higher sinter strength (MQI).

In the practical operations, when the monitoring system detected the MQI was below the standard level, the “expert system” analyzed the recorded data including combustion efficiency. If the combustion efficiency was below the normal level, a signal would be sent to adjust the operating parameters accordingly until the combustion efficiency returned to the normal working condition, such as initiating the O_2 injection controller for O_2 supplement to subjected area.

3.2.5 Effect of heat utilization efficiency

Heat utilization efficiency determines the amount of effective energy applied to melting process, which is another important factor to the sintering process. In filtration combustion, there exist two types of travelling fronts: heat transfer front and reaction front [28]. They propagate independently with their own speeds. Two typical travelling regimes are reaction leading and heat transfer leading, respectively. According to the filtration combustion theory, heat accumulation effect in high temperature zone reaches to the maximum when the speeds of heat transfer front and reaction front are the same. Similarly, in iron ore sintering process the heat utilization efficiency will reach to the maximum when the $HTFS$ is equal to FFS . Here we employed the η , introduced in section 2, to characterize the heat utilization efficiency (matching performance of $HTFS$ and FFS) in iron ore sintering process. **Figure 11** shows the influencing mechanism of η on MQI based on the data from our experiments and published references. The results indicated that sinter strength (MQI) was also very sensitive to η . Higher η was more beneficial to melt phase formation, leading to higher sinter strength (MQI). According to the **Eq. (2)** [27], $HTFS$ was related to the packed structure of sintering bed, air flowrate and properties of raw materials. In the practical operations, η should be maintained at near 1.0 by controlling the packed bed structure and air flowrate. For example, if the combustion rate increased, $HTFS$ should be raised simultaneously by adopting a loose packed bed structure or reducing the bed height properly.

4. Discussion

Except for strength, reducibility is another aspect of sinter quality. The improvement of sinter

reducibility is beneficial for reducing coke breeze ratio in liquid-iron making process. Yasumoto [35] adopted the cooling rate (CR) from the peak temperature to 1100 °C to evaluate the reducibility. The results suggested CR was an effective indicator of reducibility. We collected data from published references to reveal the relation between CR and the FeO content or the Japanese industrial standards-reducibility index ($JIS-RI$), as shown in **Fig. 12**. It was known that FeO content had a negative correlation with reducibility. The plotted profiles suggested that the sinter reducibility was highly relied on the CR . What has to be pointed out is that versatily empirical correlations of reducibility and strength for engineering applications are very difficult to obtain because of the complexity of physical and chemical reactions involved in the sintering process, as well as the differences of the experimental materials and conditions. As a result, on-line control is a substantial option to optimize the process regarding fuel consumption, product sinter quality and productivity.

Based on the reference case analysis, parametric studies and above discussion, the authors tried to propose a conceptual on-line control system of sintering performance, as shown in **Fig. 13**. The newly introduced objective parameters (MQI , CR , combustion efficiency and η) were integrated into the monitoring system. Employing the monitored parameters as input conditions, a simple code would be executed to evaluate the sintering performance. After that, expert system which was the policy maker would send recommended signals to the executive actuators to adjust the corresponding parameters accordingly. Actually, giving a wise action was quite difficult for the expert system because it was a tough work to balance the strongly coupled parameters in sintering process. This problem should be further investigated. We may resort to the fuzzy theory and artificial intelligence method [36]. In fact, expert system needs some training in commercial operation or numerical simulation. Traditionally, varying fixed carbon content, air flowrate, bed height, grate moving speed and fuel reactivity are the effective actions to control sintering performance. Additionally, gaseous fuel [17] and O_2 [16] injection techniques provided another options for the on-line control. According to the monitored MQI , we can optimize the gaseous fuel and O_2 injection rates at different positions to achieve the uniform sintering. Thus, with the help of the conceptual on-line control system, it's promising to reduce the sinter quality fluctuation and optimize the heat distribution for uniform sintering process.

5. Conclusions

This paper focused on bridging the process parameters and real sinter quality for engineering applications, which was substantial for both parameters optimizing in numerical simulation and on-line control of sinter quality. The *MQI* combining the peak temperature and *DTMT* was used and verified to characterize sinter strength in this paper. The effects of three operating parameters (fixed carbon content, sintering pressure and fuel reactivity) on *MQI* were investigated. Furthermore, the influencing mechanisms of combustion and heat utilization efficiencies on *MQI* were clarified. Finally, we even proposed a conceptual design for the on-line control of sinter quality. The major findings were as follows:

(1) In comparison with the peak temperature and *DTMT*, the *MQI* was more comprehensive and reliable to characterize sinter strength. The results indicated that the yield would increase with the rise of *MQI*. The similar trend was also found after reproducing the data from published references and plotting them in a same map. Furthermore, the relation between sinter yield and *MQI* was further confirmed in an extensive range by varying the fixed carbon content, sintering pressure and fuel reactivity. Consequently, the *MQI* was recommended as the bridge of process parameters and real sinter strength for engineering applications.

(2) The sinter strength (*MQI*) was very sensitive to the operating parameters of fixed carbon content, sintering pressure and fuel reactivity. Moreover, the combustion and heat utilization efficiencies also greatly affected the *MQI* under the comparable situations. The monitoring of the above three parameters would provide a powerful support for the transparency of sintering process “black-box” and optimization of sinter quality.

(3) A conceptual design of sinter quality on-line control system was proposed in this paper. Compared with the previous ones, it was promising to reduce the sinter strength fluctuation and achieve uniform sintering with the help of monitored *MQI* and newly developed gaseous fuel and O₂ injection techniques.

The elementary research on bridging the process parameters and real sinter quality for engineering applications was conducted in this paper. We mainly discussed the relation between sinter strength and process parameters. However, improvement of sinter reducibility is an effective method for reducing carbonaceous materials consumed in the blast furnace. Therefore, detailed

studies on bridging sinter reducibility and process parameters should be carried out in the future.

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Table Captions

Table 1 Experimental conditions arrangement

Table 2 Sintering time at different experimental conditions

Table 3 Size distribution of solid fuels

Figure Captions

Fig. 1 Comparison of heat distribution of conventional case and ideal case

Fig. 2 Definitions of key parameters [27]

Fig. 3 Temperature-time profiles in reference case (Case 1)

Fig. 4 Heat pattern of melting zone in sintering bed (Case 1)

Fig. 5 Analogy between MQI and work

Fig. 6 Relation of MQI and sinter strength

Fig. 7 Testing results at different fixed carbon content

Fig. 8 Testing results at different sintering pressures

Fig. 9 Testing results at different fuel reactivity

Fig. 10 Effect of combustion efficiency on MQI

Fig. 11 Relation between η and MQI

Fig. 12 Relation between CR and reducibility

Fig. 13 Conceptual design of control system

Table 1 Experimental conditions arrangement

Experiment no.		No. 1			No. 2			No. 3		
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
Experimental conditions	Coke/Charcoal (%)	100/0	100/0	100/0	100/0	100/0	100/0	100/0	60/40	20/80
	Total fixed carbon (%)	3.48	3.26	3.70	3.48	3.48	3.48	3.70	3.70	3.70
	Ignition pressure (kPa)	5	5	5	5	6	7	5	5	5
	Sintering pressure (kPa)	10	10	10	10	12	14	10	10	10

Table 2 Sintering time at different experimental conditions

Cases	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
Sintering time (s)	990	950	1000	990	950	830	1000	970	855

Table 3 Size distribution of solid fuels

Size distribution	0-1 mm	1-2 mm	2-3 mm	3-4 mm	4-5 mm
Mass fraction	53.45%	19.61%	21.03%	5.58%	0.33%

(a) Heat distribution of conventional case

(b) Heat distribution of ideal case

Fig. 1 Comparison of heat distribution of conventional case and ideal case

Fig. 2 Definitions of key parameters [27]

Fig. 3 Temperature-time profiles in reference case (Case 1)

(a) Isotherms in the melting zone

(b) Reconstructed temperature contour of melting zone in sintering bed

Fig. 4 Heat pattern of melting zone in sintering bed (Case 1)

(a) Analyses of object movement and forces

(b) Calculation of effective work on object

Fig. 5 Analogy between *MQI* and work

(a) Effects of peak temperature, $DTMT$ and MQI on yield in Case 1

(b) Effect of MQI on several strength parameters in published references

Fig. 6 Relation of MQI and sinter strength

(a) Local MQI evolutions at different fixed carbon content

(b) Air flowrate at different fixed carbon content

(c) Relation between MQI and yield at different fixed carbon content

Fig. 7 Testing results at different fixed carbon content

(a) Local MQI evolutions at different sintering pressures

(b) Air flowrate at different sintering pressures

(c) Relation between MQI and yield at different fixed sintering pressures

Fig. 8 Testing results at different sintering pressures

(a) Local MQI evolutions at different fuel reactivity

(b) Air flowrate at different fuel reactivity

(c) Relation between MQI and yield at different fuel reactivity

Fig. 9 Testing results at different fuel reactivity

(a) Relation between $[CO_2]/[CO_2+CO]$ and MQI [30]

(b) Relation between $[O_2]$ and MQI

Fig. 10 Effect of combustion efficiency on MQI

Fig. 11 Relation between η and MQI

Fig. 12 Relation between *CR* and reducibility

Fig. 13 Conceptual design of control system