Effects of Coal Inertinite Size on Coke Strength

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In order to improve coke strength by the technique of coal size control, it is essential to understand the relationship between inertinite size and coke strength. The size and area of the inertinite in coke were measured with a microscope and an image analysis technique and the effect of the inertinite size on coke strength was investigated. Moreover, the reason why DI_{150} leveled off at an inertinite size of 1.5 mm was investigated.

The results are follows.

1) When the inertinite size is between about 1.5 mm and 5 mm, the surface breakage product (DI_{150}) decreases as the size of inertinite in coke diminishes. When the inertinite size is over about 5.0 mm, volume breakage product (DI_{6-15}) decreases as the inertinite size diminishes.

2) Effects of 1% increase/decrease of different size groups of inertinite on DI_{150} and DI_{6-15} were clarified.

3) According to Hertzian contact theory and Griffith equation, it is estimated that cracks under 0.5 mm do not grow by fall of coke in the drum tester. The critical inertinite size (1.5 mm) is an appropriate value for this critical crack size (0.5 mm), because the size of the crack around the inertinite grain is equal to or smaller than the size of the inertinite grain.

KEY WORDS: coke; coal; coke strength; inertinite size; image analysis; tensile stress; crack; Griffith equation; Hertzian contact theory.

1. Introduction

The emphasis in the operation of Japanese blast furnaces is moving to decreasing the reducing agent ratio and increasing furnace productivity with the aim of decreasing CO₂ emissions and boosting production. It is feared, however, that fine coke accumulates inside a blast furnace when a low reducing agent ratio is targeted, and some point out that this tends to intensify as furnace productivity increases.1,2) The development of technology for producing high-strength coke with excellent abrasion resistance is therefore of great importance to achieve a low reducing agent ratio and high productivity during blast furnace operation.

A wide variety of techniques have been developed to produce high-strength coke1–6); of which the coal size control technology is a typical example.7,8) Generally speaking, crushing coal more finely before charging it into a coke oven is effective in improving the strength of the product coke. When the coal size diminishes excessively, however, the coke oven operation is adversely affected for reasons such as a decrease in the charging coal density, which leads to the consequent fall in charging weight per coking chamber and lower coke strength, and an increase in the carry-over of fine coal. Consequently, to enhance coke strength efficiently, it is necessary to limit coal crushing to the minimum required extent.

Coal crushing is generally considered effective in improving coke strength, mainly because of the decreased size of inertinite in coal.7,8) Hence, to improve coke strength while avoiding excessive crushing of coal, it is important to understand the relationship between the inertinite size and coke strength as much in detail as possible.

In this relation, Miura et al. produced coke by blending inertinite-concentrated coal of different sizes at a prescribed mixing ratio, and, based on the results, reported the relationship between the size of the inertinite-concentrated coal and the coke strength,9) while Asada et al. did likewise using inertinite-concentrated coal classified into two size ranges, below 0.25 mm and from 0.5 to 1.0 mm, and reported the relationship between the size of the inertinite-concentrated coal and the coke strength (in terms of the ratio of coke breeze generated).9) These reports, however, described only the relationship between the size of the inertinite-concentrated coal and the coke strength; while the size of inertinite was not measured directly, nor was the relationship between the inertinite size and coke strength evaluated. Therefore, the relationship between the inertinite size and coke strength has not been sufficiently clarified yet.

In view of this situation, the authors sieved and classified inertinite-concentrated coal into size ranges of 0.1 to 0.3, 0.3 to 0.6, 0.6 to 1.2, 2.0 to 4.0, 5.0 to 7.0 and 10 to 15 mm, produced coke by blending one of these size groups of inertinite-concentrated coal at a prescribed ratio, actually measured the size of inertinite grains in coke via image analysis...
of photomicrographs of the coke specimens produced, and examined the effects of the inertinite size on the coke strength (in terms of drum indices DI$_{150}^{150}$–6 and DI$_{150}^{150}$–15).

2. Experiment

2.1. Preparation of Coal Specimens

Figure 1 illustrates the method used to prepare the specimens of inertinite-concentrated coal. Firstly, raw material coal from a storage yard, Coal A, (with a total inertinite content of 35.6%) was sieved with a 15-mm screen, the oversize lump coal was crushed and then sieved with a 6-mm screen. The oversize coal 6 mm or more in size thus obtained will be hereinafter called “Coal B” (inertinite-concentrated coal).

Then, to prepare specimens of inertinite-concentrated coal of different sizes but with the same content of maceral components, Coal B was crushed and sieved into the following size groups: 0.1 to 0.3, 0.3 to 0.6, 0.6 to 1.2, 2.0 to 4.0, 5.0 to 7.0 and 10 to 15 mm. Here, in order to homogenize the maceral components of the different size groups, Coal B was crushed lightly in a mortar in a manner to minimize the generation of fine coal smaller than the lower limits of each size range, and then sieved. Note that specimens 10 to 15 mm in size were prepared by sieving the oversize 6 mm or more in size with a 10-mm screen and restricting the oversize to 10 to 15 mm.

Table 1 shows the proximate analysis results, total dilatation and maximum fluidity of Coals A and B. It is clear from the table that Coal B contained less volatile matter and more ash than Coal A, and showed little or no dilatation and fluidity. Figure 2 shows the percentage contents of the maceral components of Coal A and the different size groups of Coal B. The graph shows that the inertinite content was markedly high in the Coal B specimens in comparison with that of Coal A, and all the size groups of Coal B had substantially equivalent contents of maceral components.

2.2. Carbonization Test

2.2.1. Coal Blending

Table 2 shows the blending ratio and coal size condition. While blend No. 1 was composed entirely of raw coal A crushed to 1.5 mm or less, blend Nos. 2 to 7 contained one of the size groups of Coal B by 15%. (The coke made from blend Nos. 1 to 7 will hereinafter be called Coke Nos. 1 to 7, respectively.)
2.2.2. Carbonization Condition

Each of the coal mixtures was charged into a furnace 420 mm wide, 400 mm high and 600 mm long, heated electrically from both sidewalls, and carbonized for 18.5 h into coke; the temperature of the electric heating elements was controlled such that the heat pattern of the charged coal was the same as that of coal carbonized in a commercial coke oven operating at a flue temperature of 1250°C. The coal moisture was 3% and the charging density was 0.85 t-dry/m³. The coke after carbonization was quenched to room temperature in a nitrogen atmosphere.

2.3. Coke Analysis

A lump of coke was cut out as shown in Fig. 3 from each of the coke produced in the above manner and cut at four planes parallel to the heating walls at intervals of 35 mm. Then the section surfaces were impregnated with resin and polished for microscopic observation. Two photomicrographs, each 18.5×14.5 mm, were taken at each of the four cut surfaces (eight photomicrographs in total for each coke specimen).

Inertinite grains seen in the sectional photomicrographs were visually identified and marked, and their grain distribution was measured using commercially available software for image analysis. As an example, Fig. 4 shows one of the photomicrographs before and after the marking of inertinite grains at a section surface of Coke No. 5; the portions in dark gray are pores, those in light gray are coke and others in white are inertinite grains.

In addition to the microscopic observation, the coke quenched to room temperature underwent drop impacts three times from a height of 2 m within a shutter tester, and the drum index according to JIS K 2151 was obtained for each coke specimen.

3. Results

3.1. Relationship between the Size of Inertinite-concentrated Coal and Drum Index of Coke

Figure 5 shows the relationship between the size of the inertinite-concentrated coal (Coal B) and the drum index DI_{150}^{150} of the coke obtained. Here, the coke specimens are plotted along the horizontal axis at the respective mean values of the size groups of Coal B. The graph shows that DI_{150}^{150} increases as the grain size of Coal B decreases, but the index does not increase further when the size of Coal B falls to below 1 mm.

In Fig. 6, part (a) shows the relationship of the size of Coal B with the ratio of coke breeze smaller than 6 mm (DI_{150}^{150}–6) after the drum test, and part (b) that with the ratio of coke breeze 6 to 15 mm in size (DI_{150}^{150}–15). Here, DI_{150}^{150}–6 and DI_{150}^{150}–15 represent, respectively, the product of surface breakage and that of volume breakage, and their relationship with DI_{150}^{150} is expressed as follows:

$$\text{DI}_{150}^{150} = 100 - (\text{DI}_{150}^{150}–6 + \text{DI}_{150}^{150}–15) \ldots \ldots \ldots \ldots (1)$$
As seen in Fig. 6, $\text{DI}^{150}_{6-6}$ decreases when the size of Coal B decreases within the range 6 to 1 mm, and $\text{DI}^{150}_{6-15}$ decreases only within the size range of Coal B down to 3 mm. The above indicates that the size ranges of Coal B effective for decreasing the generation of coke breeze of respective size are not identical.

3.2. Size Distribution of Inertinite Grains in Coke

Figure 7(a) shows the size distribution of inertinite grains in coke obtained through image analysis of the sectional photomicrographs of the coke specimens. The inertinite size along the horizontal axes of the graphs is the absolute maximum length defined as the largest distance between two points arbitrarily selected on the contour of an inertinite grain, and the percentage of inertinite in coke along the vertical axes is the percentage area of inertinite grains in relation to the total sectional area in the photomicrographs analyzed. Figure 7(b) shows the size distribution of the inertinite originating from Coal B in coke calculated by subtracting 85% of the inertinite size distribution in Coke No. 1 (made from 100% Coal A crushed to below 1.5 mm) from the inertinite size distribution in each of Coke Nos. 2 to 7. The graph shows that the size distribution of the inertinite originating from Coal B in each of Coke Nos. 2 to 7 peaks substantially within the range of the size group of Coal B that was mixed at the material coal preparation.

Figure 8 shows the total percentage of inertinite originating from Coal B in coke; whereas it is roughly 10% with
4. Discussion

4.1. Effects of the Inertinite Size on Coke Strength

This section deals with the size ranges of inertinite in coke that affect its drum indices $(D_{150}^{6-15})$. In addition, classifying inertinite grains of different sizes in coke into prescribed size groups, it also deals with the effects of a 1% increase/decrease of the different size groups of inertinite in coke on its drum indices $(D_{150}^{6-15})$.

4.1.1. Size Ranges of Inertinite in Coke Having Effects on Drum Indices

Figure 6 shows that Coke Nos. 2, 3 and 4 showed substantially the same values of $D_{150}^{6-15}$ and likewise Coke Nos. 6 and 7, though at a different level; and from this and Fig. 7(b), one can presume that, when the inertinite size changes in either of the ranges of less than about 1.5 mm and more than about 5.0 mm, its effects on $D_{150}^{6-15}$ would be insignificant. Figure 6 also shows that Coke Nos. 2 to 5 exhibited substantially the same values of $D_{150}^{6-15}$ this and Fig. 7(b), lead to the presumption that, when the inertinite size changes within a range of less than about 5.0 mm, its effects on $D_{150}^{6-15}$ would also be insignificant.

The above indicates that the amount of surface breakage product or $D_{150}^{6-15}$ decreases with decreasing inertinite size in the range between 5.0 and 1.5 mm, but that the decrease in the inertinite size in the range below 1.5 mm or over 5.0 mm causes little change to $D_{150}^{6-15}$. On the other hand, the amount of volume breakage product or $D_{150}^{6-15}$ decreases with decreasing inertinite size in the range over 5.0 mm but the decrease in the inertinite size in the range below 5.0 mm causes little change to $D_{150}^{6-15}$.

4.1.2. Effects of 1% Increase/Decrease of Different Size Groups of Inertinite on Drum Indices $(D_{150}^{6-15})$

Firstly, the percentage areas of inertinite grains of sizes 1.6 $(10^{0.2})$ to 3.2 $(10^{0.5})$ mm, 3.2 to 5.0 $(10^{0.7})$ mm, 5.0 to 10 mm and 10 mm or more relative to the total sectional area examined by image analysis were calculated from the inertinite size distribution of Coke Nos. 2 to 7 shown in Fig. 7(b).

Secondly, assuming that defects other than inertinite of all coke specimens were the same, and that the effects of the size groups of inertinite on $D_{150}^{6-15}$ and $D_{150}^{6-15}$ exhibit additivity, the authors considered that $D_{150}^{6-15}$ and $D_{150}^{6-15}$ could be estimated using the following equations:

\[
D_{150}^{6-15}(\sim) = a \times \{1.6–3.2 \text{ mm-%}\} + b \times \{3.2–5.0 \text{ mm-%}\} + e \times \{5.0–10 \text{ mm-%}\} + e' \times \{+10 \text{ mm-%}\}..........................(2)
\]

where: the terms between $\{\}$ indicate the percentage areas of different sized groups of inertinite; coefficients $a$, $b$, $c$, $c'$ and $d'$ represent the effects of the respective size groups of inertinite on $D_{150}^{6-15}$ and $D_{150}^{6-15}$ when their percentage area increases or decreases by 1% in each case; constant $e$ is the average of $D_{150}^{6-15}$ of Coke Nos. 2 to 4 (12.19); and constant $e'$ is the average of $D_{150}^{6-15}$ of Coke Nos. 2 to 5 (1.27).

Lastly, using least squares regression analysis, the values of coefficients $a$, $b$, $c$, $c'$ and $d'$ (coefficients to express the effects of 1% increase/decrease in the amounts, or percentage sectional areas, of the respective inertinite size groups over $D_{150}^{6-15}$ and $D_{150}^{6-15}$) were calculated so that the correlation coefficient between the actually measured $D_{150}^{6-15}$ and that estimated from Eq. (2) and that between actually measured $D_{150}^{6-15}$ and that estimated from Eq. (3) became the
highest.

Parts (a) and (b) of Fig. 9 compare the estimated and measured values of DI_{150–6} and DI_{150–6–15}, respectively, while Fig. 10 shows the change of DI_{150–6} and DI_{150–6–15} resulting from a 1% increase/decrease of the different size groups of inertinite in coke. The estimated change of DI_{150–6} resulting from a 1% increase/decrease of inertinite is as follows: that of inertinite 1.6 to 3.2 mm in size is 0.09 (a); that of inertinite 3.2 to 5.0 mm in size is 0.19 (b); and that of inertinite 5.0 mm or more in size is 0.23 (c) respectively. On the other hand, the estimated change of DI_{150–6–15} resulting from the same is as follows: that of inertinite 5.0 to 10 mm in size is 0.08 (c’); and that of inertinite 10.0 mm or more in size is 0.13 (d’).

As described above, the size of inertinite in coke was actually measured via image analysis of the sectional photomicrographs of coke specimens, and the effects of a 1% increase/decrease in the amounts of different size groups of inertinite on coke strength (in terms of DI_{150–6} and DI_{150–6–15}) were clarified.

4.2. Critical Inertinite Size

It became clear from Sec. 4.1 that DI_{150–6} would not decrease, even when the size of inertinite decreased to less than about 1.5 mm. Then, the authors defined a critical inertinite size as the value of inertinite size beyond which the decrease in DI_{150–6} with decreasing inertinite size would not proceed further, and studied the reason why it was near 1.5 mm.

4.2.1. Cracking Near Inertinite Grain

Nishimura et al. reported that inertinite and vitrinite demonstrated different contraction behaviors, and suggested that this led to cracking at the interfaces between these maceral components. Davidge et al. reported that cracks having the sizes close to those of the grains would form around the grains with different contraction characteristics, and that the crack size would change in proportion to the grain size. Figure 11 shows photomicrographs of cracks having formed near inertinite grains. Part (a) of Fig. 11 shows cracks developing radially from an inertinite grain of a fusinite, and part (b) shows cracks caused by the exfoliation of an inertinite grain from the surrounding texture. The size of such cracks is considered to decrease as the size of the inertinite decreases.

The size and position of these cracks are expected to change depending on factors such as the difference in contraction coefficients between the inertinite grain and surrounding components, the adhesive properties of both and the elastic coefficient of the surrounding components. However, since cracks occur three-dimensionally, it is difficult to measure their real size based on sectional observation, which is two-dimensional. While more accurate, three-dimensional measurement of cracks remains a future task, qualitative and sectional observation through a microscope shows that the size of cracks occurring near an inertinite grain is mostly the same as or smaller than the size (absolute maximum length) of the grain, in other words, [the size of cracks near an inertinite grain]=[the size of the inertinite grain].

With respect to the strength of a brittle material like coke, when it has a crack of length 2c, the Griffith equation for the fracture under planar tensile stress is given as follows:

$$K = \sigma \sqrt{\pi c}$$

where $K$ [Pa m$^{1/2}$] is the fracture toughness, $\sigma$ [Pa] is the tensile stress, and $c$ [m] is the half-length of the crack. Here the critical crack size is defined as the minimum size of the crack that begins to develop under a certain tensile stress. A crack develops when the value of the right side $\sigma \sqrt{\pi c}$ is equal to that of the left side $K$. Here, assuming that the Griffith equation is applicable locally to a crack near an inertinite grain, it is possible to calculate the critical crack size 2c from the fracture toughness $K$ of coke and the ten-
sile stress $s$ imposed on the coke.

4.2.2. Distribution of the Tensile Stress Applied to Coke

The authors calculated the distribution of tensile stress acting on the coke at a drum test. Coke is considered to fracture at a drum test, mainly due to the impact of its collision with the steel plate of the drum tester. The stresses to which a lump of coke is subjected in such circumstances include compression stress applied to the contact surface, shear stress within the lump and tensile stress acting on the vicinity of the contact surface periphery.\textsuperscript{14}) Since tensile stress is considered to be the main cause of breakage in brittle materials like lumps of coke,\textsuperscript{14}) the authors assumed that a lump of coke would break due to the tensile stress applied to its surface. (The compressive stress at the center of the contact surface is about ten times as much as the tensile stress in the vicinity of the contact surface periphery, in other words, all the main stresses are in the compressive direction, and its contribution to crack development is presumably insignificant.\textsuperscript{15}) It has to be noted, however, that fine particles tens to several hundreds of micrometers in size may arise from the convex of coke substrate in the contact surface.)

With respect to a case where a spherical lump of coke 50 mm in diameter falls from a height of 1 m to collide with a steel plate, like in a drum tester as illustrated in Fig. 12, the distribution of the tensile stress applied to the surface of the coke lump was calculated based on the Hertzian contact theory.\textsuperscript{14,16}) Here, the direction parallel to the steel plate is called the $r$-direction, and that perpendicular to it the $z$-direction.

According to the Hertzian contact theory, the relationship between a load $P$ [N] imposed on a coke lump and its deformation $\delta$ [m] resulting from the load is expressed as follows:

$$P=A\delta^{3/2}$$ .............................................................(5)

$$A=\frac{2\sqrt{2}}{3}\left(1-\frac{\nu_1^2}{Y_1}+\frac{1-\nu_2^2}{Y_2}\right)^{-1}$$

where $Y$ [N/m\textsuperscript{2}] is Young’s modulus, $\nu$ [–] is the Poisson ratio, the suffixes 1 and 2 indicating the coke lump and steel plate, respectively, and $dp$ [m] is the diameter of the coke lump.

Assigning the value to the Eq. (7), $\eta=1$, $E$ (the potential energy of the falling coke lump)=$0.64$ N·m, $Y_1$ (the apparent Young’s modulus of the coke lump)=$1.5\times10^{10}$ N/m\textsuperscript{2},\textsuperscript{17} $\nu_1$ (the Poisson ratio of the coke lump)=$0.3$, $Y_2$ (the Young’s modulus of the steel plate)=$2.1\times10^{11}$ N/m\textsuperscript{2}, $\nu_2$ (the Poisson ratio of the steel plate)=$0.3$, the compressive load $P$ acting on the coke lump is approximately 3 400 N.

Now, according to the Hertzian contact theory, the radius $a$ [m] of the contact surface and the deformation $\delta$ [m] are given by the following equations, respectively:
Assigning the values of the compressive load \( P \) [N], radius of the coke lump \( R \) [m], the above Young's moduli \( Y_1 \) and \( Y_2 \) [N/m²] and Poisson ratios \( \nu_1 \) and \( \nu_2 \) in these equations, the deformation amount \( \delta \) is estimated to 0.46 mm and the radius \( a \) of the contact surface is 3.42 mm.

Using Hertzian contact theory, the maximum compressive stress \( q_0 \) [Pa] applied to the center of the contact surface and the maximum tensile stress \( \sigma_r \) [Pa] applied to the region near its periphery are given by the following equations, respectively:

\[
q_0 = \frac{3P}{2\pi a^2} \quad \text{(10)}
\]

\[
\sigma_r = \frac{1-2\nu}{3} q_0 \quad \text{(11)}
\]

As a result of all the above, the maximum compressive stress \( q_0 \) in the \( z \)-direction at the center of the contact surface is estimated at 142 MPa, and the maximum tensile stress \( \sigma_r \) in the \( r \)-direction at its periphery is 19 MPa. It has to be noted in relation to the above that even when the diameter \( dp \) of the coke lump changes, the maximum compressive stress \( q_0 \) and maximum tensile stress \( \sigma_r \) remain constant, because the radius \( a \) of the contact surface changes according to the change in the compressive load \( P \).

Next, in consideration of the stress distribution at the surface of a spherical body in the case of point contact,\(^5\) the authors calculated the distribution of stress in the \( r \)-direction acting on the coke lump surface. Figure 13 shows the result. The horizontal axis represents the distance of a given point on the surface of the coke lump from the center of the contact surface, and the vertical axis the tensile stress in the \( r \)-direction, a negative value indicating compressive stress.

The graph shows that the maximum compressive stress within the contact surface is 114 MPa, a maximum tensile stress of 19 MPa in the \( r \)-direction is applied to the periphery of the contact surface, and the tensile stress decreases gradually with increasing the distance from the contact surface.

4.2.3. Critical Inertinite Size

Part (a) of Fig. 14 shows the distribution of the tensile stress \( \sigma_r \) acting on the surface of the coke lump near the periphery of the contact surface, and part (b) that of the critical crack size \( 2c \). Here, the distribution of \( 2c \) was calculated by assigning the distribution of tensile stress \( \sigma_r \) obtained in the preceding Subsec. 4.2.2 and \( K \) (the fracture toughness of coke)=0.5 MPa·m\(^{0.5}\))\(^{17\)} into the Griffith Eq. (4).

For example, with respect to Fig. 14(b), when there is a surface crack 6 mm or more in size and perpendicular to both \( r \)- and \( z \)-axes at a surface position 5 mm from the center of the contact surface, a crack will develop, but when the size of the crack is less than 6 mm, it will not. In other words, Fig. 14(b) shows that a crack will grow in the zone above the \( 2c \) curve, while below the curve, it will not.

One can understand the following from Fig. 14(b):

1) When the crack size decreases with decreasing inertinite size, the zone in which a crack grows is limited to a region nearer to the contact surface, meaning a consequent drop in the probability of crack growth and increased coke strength.

2) The smallest critical crack size along the periphery of a contact surface, where tensile stress peaks, is approximately 0.5 mm. This means that a crack smaller than about 0.5 mm in a coke lump will not grow as a result of a fall in a drum tester. Moreover, as described in Subsec. 4.2.1, the size of a crack near an inertinite grain is substantially the same as or smaller than that of the inertinite grain. Therefore, in relation to the minimum critical crack size of 0.5 mm, it would be reasonable to set the critical inertinite size at 1.5 mm.
5. Conclusion

The effects of inertinite size on coke strength (in terms of the drum indices D150\textsubscript{1–6} and D150\textsubscript{6–15}) were studied by measuring the size of inertinite grains in coke through image analysis of sectional photomicrographs of coke specimens. Also studied was the reason why the value of inertinite size at which the decrease in D150\textsubscript{1–6} with decreasing inertinite size comes to a halt (critical inertinite size) was approximately 1.5 mm. The following conclusions were obtained:

1) The amount of surface breakage product or D150\textsubscript{1–6} decreases with decreasing inertinite size in the range between 5.0 and 1.5 mm. On the other hand, the amount of volume breakage product or D150\textsubscript{6–15} decreases with decreasing inertinite size in the range over 5.0 mm.

2) The effects of 1% increase/decrease in the amount (sectional percentage area) of inertinite in coke on D150\textsubscript{1–6} and D150\textsubscript{6–15} were clarified within the inertinite size ranges mentioned in (1) above where D150\textsubscript{1–6} and D150\textsubscript{6–15} decreased.

3) Based on the Hertzian contact theory and Griffith equation, it is inferred that a crack 0.5 mm or less in size in a coke lump will not grow as a result of a fall in a drum tester. Based on the fact that the size of a crack formed near an inertinite grain is equal to or smaller than that of the inertinite grain, it would be reasonable to set the critical inertinite size at 1.5 mm in relation to a critical crack size of 0.5 mm.

REFERENCES

7) C. Abramovskii: Glückauf, 91 (1955), 714.