Three-Dimensional Shape Measurement of Coke Using a Medical X-Ray CT Scanner

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To investigate the relationship between the three-dimensional characteristics of the fissure and coke size, an image processing method was developed for 3D medical computed tomography images to extract the fissure plane. The three-dimensional volume of the coke fissure showed a poor correlation with the coke size, whereas the plane area of the fissure showed a good correlation with the size of the coke that was not subjected to rotational impact. On the other hand, the relationship between the coke size and fissure plane area under rotational impact is not perfect, and it may be necessary to consider the effects of smaller cracks.

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Introduction/Background

Coke plays an essential role in maintaining the flow of liquid and gas in a blast furnace; therefore, the size of the coke is an essential quality characteristic.[1–3] Generally, larger coke particles are more suitable for blast furnace operations. Hence, there is a crucial need for techniques to control the particle size of coke, and it is necessary to understand the factors that determine these sizes.

Several researchers have studied the relationship between the formation of fissures in coke cake and the size of the coke.[4,5] However, most of these studies were conducted in two dimensions using cross-sectional images of the fissures. Conversely, coke fissures realistically have a three-dimensional structure. Therefore, there is a significant need for three-dimensional measurements to evaluate the amount and shape of coke fissures, which helps to better understand the nature of fissure formation, and to investigate the size of the coke.

A medical computed tomography (CT) scanner was used to obtain more detailed information about the three-dimensional shapes of coke and fissures. The key feature of a medical CT scanner is its ability to scan a wide area without causing damage. For example, numerous coke particles were scanned with a wide field of view to ensure representativeness, and the size and flattening ratio of coke shapes were evaluated by using image analysis.[6] Medical x-ray CT and three-dimensional image analysis appear to be promising tools for investigating fissures contained within coke cakes.

In this study, a medical x-ray CT scanner was used to capture images of coke cakes. A variety of coke breeze was added to the coke cake to control the size of the coke particles. The fissures found within the coke cake were subsequently analyzed using three-dimensional image analysis software, enabling a quantitative evaluation of the fissure amounts. In particular, a novel procedure was implemented to analyze fissures as three-dimensional planes. In addition, a comparison was conducted between the area of the fissure plane and the mean size of the coke.

Experimental

Testing in a Pilot-Scale Coke Oven

Carbonization Test in a Pilot-Scale Coke Oven: Five different types of coals (50% three caking

Table 1

Condition of Coke Breeze Addition

Sample No.	Type of coke breeze	Sieved size
S0	None	None
S1	Coke breeze from coke dry quenching cyclone	0.42 mm (mean size)
S2	Sieved coke breeze	<0.10 mm
S3	Sieved coke breeze	0.10–0.30 mm
S4	Sieved coke breeze	0.30–0.40 mm
S5	Sieved coke breeze	0.40–0.50 mm
S6	Sieved coke breeze	0.50–0.60 mm
S7	Sieved coke breeze	0.60–1.00 mm
S8	Sieved coke breeze	>1mm

Figure 1

Medical x-ray computed tomography (CT) scanner.

coals and 50% two non-/slightly caking coals) were pulverized until the ratio under 3 mm was 82.5% to 85% and charged into a metal container. The weight averages of the volatile matter (VM) and total dilatation (TD) for the blended coal without a coke breeze were 29.2% and 113.4%, respectively. To control the coke size, 2% coke breeze was added to the blended coal. The sizes of the coke breeds are listed in Table 1. Blended coal with coke breeze was charged at a bulk density of 850 kg/m^3 dry in an electrically heated pilot-scale coke oven (420 mm wide, 600 mm long and 400 mm high) and carbonized for 18.5 hours under heating conditions equivalent to a flue temperature of 1,250°C in an actual coke oven. After carbonization, the coke cake was quenched with nitrogen.

X-Ray Scanning Using Medical CT: Images of the carbonized coke cake were obtained using medical x-ray CT equipment (TSX-201 Aquilion LB, Toshiba Medical Systems Corp.; Fig. 1). The coke cake in the metal container was placed on the bed of a medical x-ray CT scanner, and the entire container was scanned nondestructively with a slice pitch of 0.5 mm for the longitudinal direction (600 mm long). The image size for the width and height directions (420 mm wide and 400 mm high) was 512 x 512 pixels, and the resolution of the image was 1.132 mm per pixel. The tube voltage was 120 kV, the tube current was 350 mA and the irradiation time was 0.5 second.

Size Measurement of Cokes Sample: After CT scanning, the coke cake was dropped from a height of 2 m, and the coke particles were sieved. At this stage, the mean size of coke particles larger than 25 mm was measured and denoted as "MS 0 rev/+25 mm" in this article. A 10 kg coke sample was prepared for drum testing from the sieved coke. After the drum test with 30 revolutions, the coke particles were sieved and the mean size was measured. This measurement was denoted as "MS 30 rev/+25 mm" in this article.

Image Analysis

Image Analysis Method

Three-dimensional CT images of the coke cake were analyzed using the Avizo software (Thermo Scientific™ Avizo Software™, Thermo Fisher Scientific Inc.). This process enabled the identification of coke fissures and the extraction of the fissure plane. For the image analysis, cubic voxel with a side of 0.5 mm was achieved by resizing (Lanczos filtering) the original voxel, which had dimensions of width and height of 1.132 mm and length of 0.5 mm, using the functionality of the software.

Segmentation: Fig. 2 shows the process of identifying fissures in a coke cake image. In the CT data, high-density materials appeared bright, whereas spaces and low-density materials appeared dark. Thus, the coke matrix is represented as a region of high brightness, and the fissures are represented as areas of low brightness in the images. To identify fissures, Otsu's method[7] was employed to set the brightness threshold. Unfortunately, some narrow fissures could not be detected using simple thresholding. This is because the spatial change in the CT values from the coke matrix to the fissure cannot be explicitly imaged, particularly when the neighboring matrices are closely positioned. To address this, a top-hat image processing technique was used. The top-hat transformation subtracts the image produced by the opening operation (shrinking and dilating the image) from the original image. The top-hat transformation makes it possible to identify locations with relatively low brightness values as fissures when compared to the surrounding areas. Fig. 2b shows the identified fissures. Although some narrow fissures disappeared, most were clearly identified. The volume of the identified fissures was assessed by counting the number of fissure voxels.

Fissure Plane Extraction:

The application of thin-line processing to 2D images is a traditional method for quantitatively estimating the number of fissures in coke. In this study, thinner fissures were extended from a 2D image to a 3D domain, and the number of fissures was assessed quantitatively using the fissure plane area based on the length of the fissure lines, because the lines in the 2D image become planes in 3D space by stacking these images, and their lengths are translated into areas. In general, image analysis software uses 2D thin-line processes for transforming objects into simple lines; however, no software exists that can transform 3D objects into planes. Therefore, it was attempted to extract fissure planes using fundamental three-dimensional image processing techniques. The process for extracting fissures as planes is described in the following. Fig. 3 provides a schematic and an example of image processing performed on a coke cake.

I. Using brightness value settings and top-hat processing, the x-ray CT images were separated into coke and fissure (space) portions.

II. The portions of the coke extracted from I were separated into lumps. However, the coke cake matrix is mostly connected in three dimensions and algorithms that consider connectivity alone cannot separate it into lumps. Therefore, as

Figure 2

Example of an x-ray CT image of a coke cake: Original image (a) and identification result of the fissure portion (b).

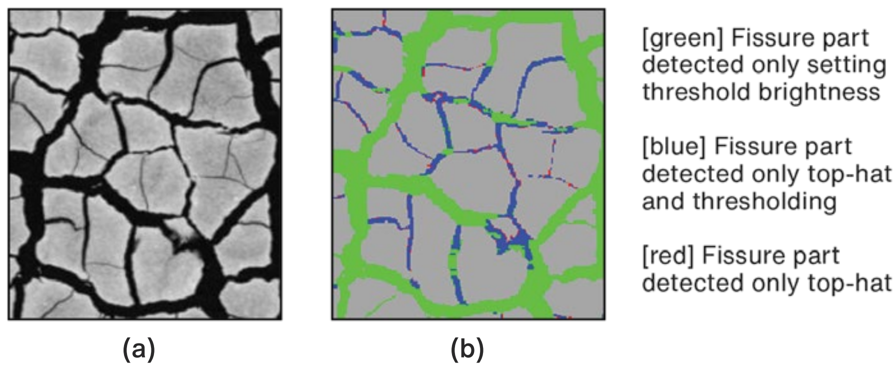


Figure 3

Example of fissure plane extraction procedure with image processing.

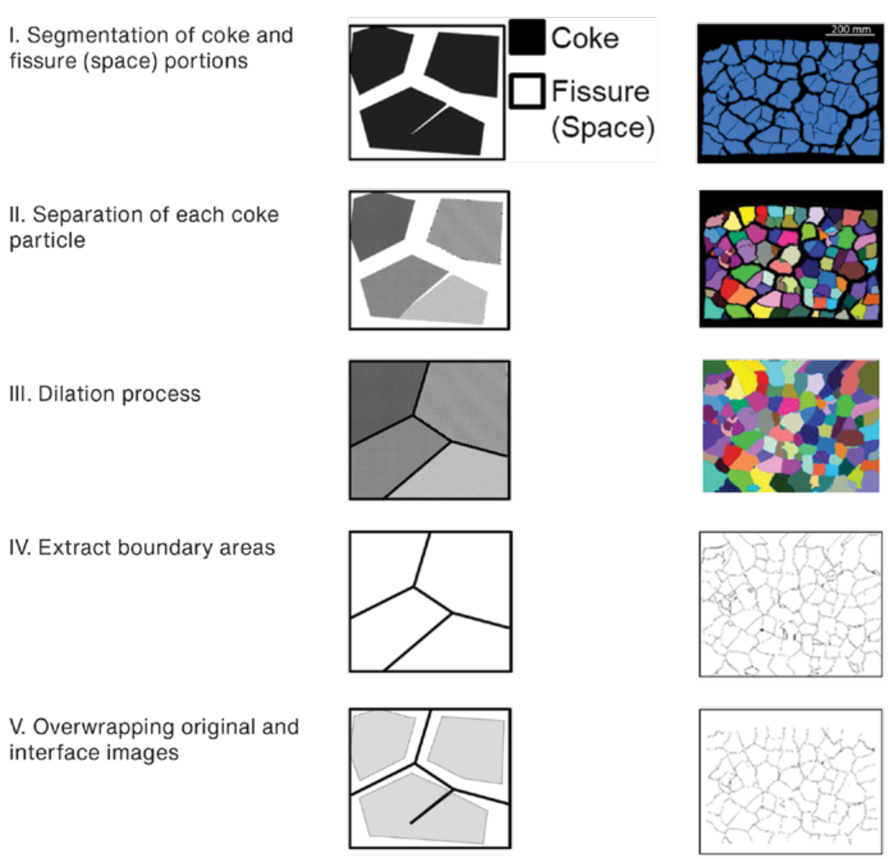
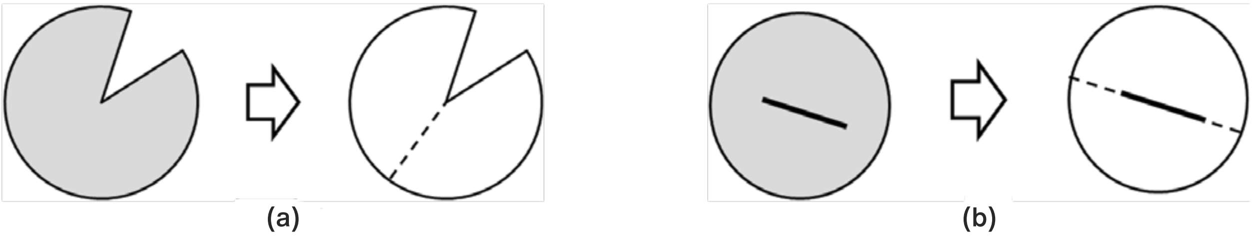


Figure 4

Schematic of separation algorithm: location of notch (a) and location of crack (b).



shown in Fig. 4, it is necessary to use image-processing techniques that separate particles at the location of the notch or where the internal fissures exist. In this analysis, the watershed method,[8] a typical algorithm, was used for particle separation.

III. Each separated part is dilated to completely fill the fissure portion.

IV. Boundaries are formed between different parts owing to the processing described in III. The boundary areas were then extracted.

V. The boundary regions extracted in IV were compared with the fissure regions in I, and the regions that were both boundary areas in IV and fissure regions in I were extracted as fissure planes.

Fig. 5 shows an example of applying the proposed method to a coke cake produced in a test coke oven, and it can be seen that three-dimensional fissure planes can be extracted. The area of the extracted fissure plane was calculated utilizing software to count number of voxels.

Results and Discussion

Effect of Coke Breeze Addition on Coke Size

Fig. 6 illustrates the effect of the coke breeze conditions on the mean size of the coke. Compared to conditions S0 and S1, the addition of coke breeze caused an increase in the mean size of the coke because the shrinkage of the coke breeze was less, and coke breeze addition caused less shrinkage. Focusing on conditions S2–7, it was observed that the larger the coke breeze, the larger the mean size of the coke. This trend is because the coke breeze decreases the shrinkage of coke,[9,10] which causes small thermal stress and fewer fissures. However, when more than 1 mm of coke breeze is added (S8), the mean coke size decreases. It is hypothesized that a larger coke breeze causes cracking, which can degrade the coke particles.

Figure 5

X-ray CT image of coke cake carbonized by pilot coke oven (a) and fissure plane in coke cake (b).

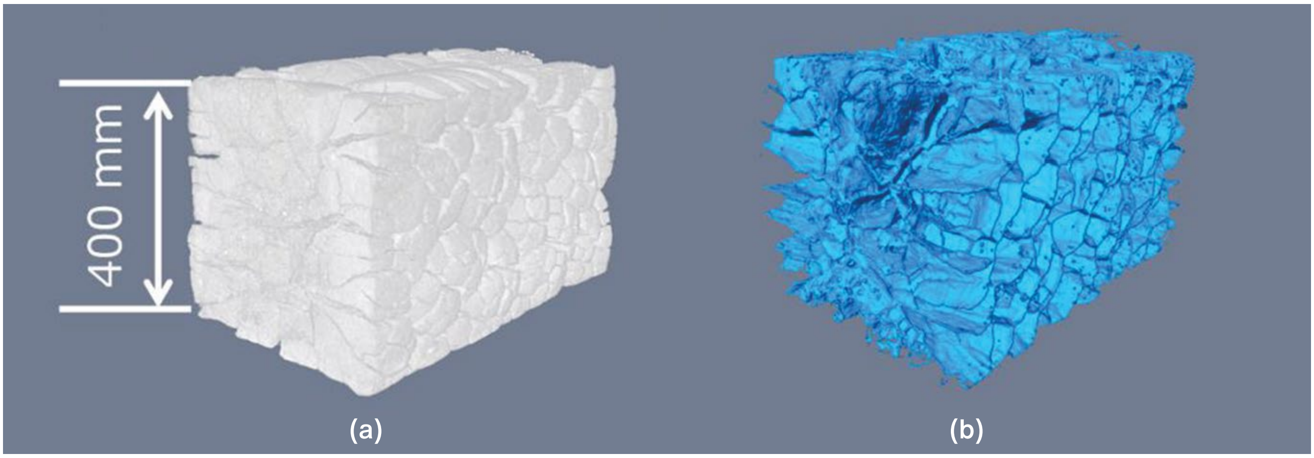
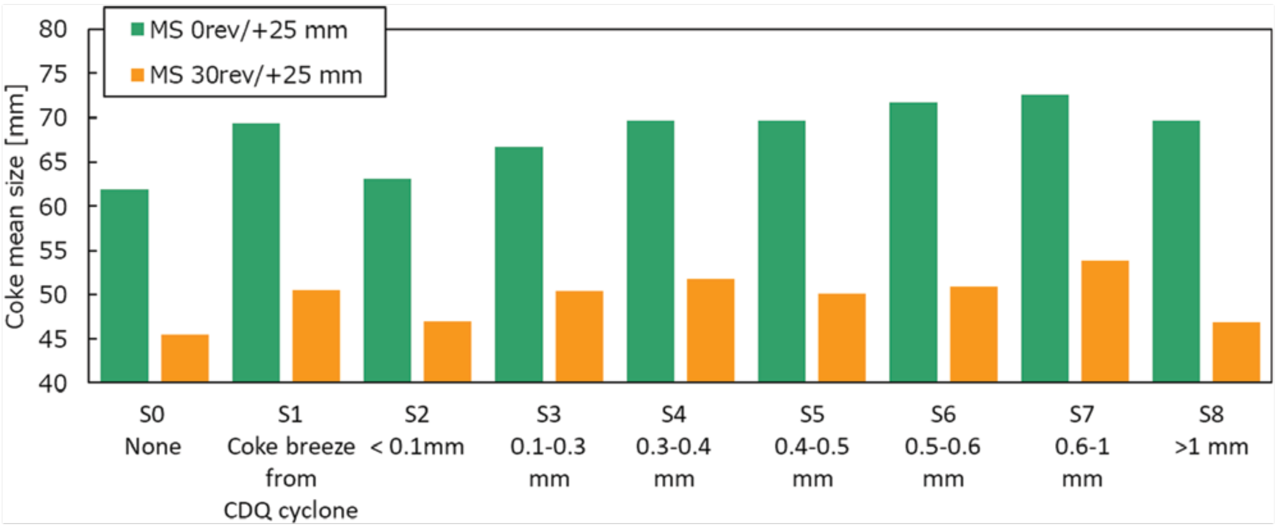


Figure 6

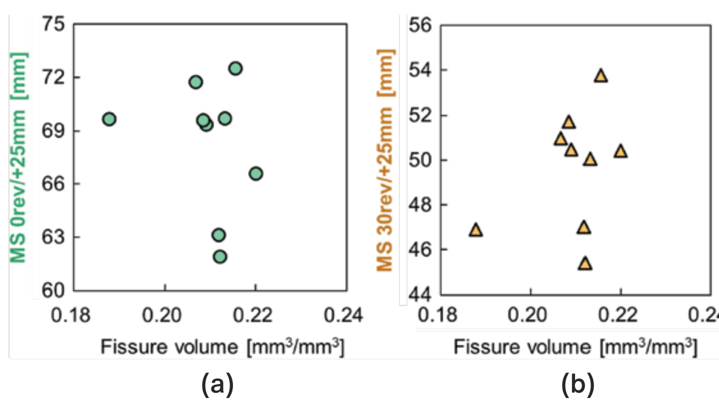
Coke particle size under each coke breeze additive condition.



Relationship Between Fissure Volume and Coke Size: Fig. 7 illustrates the relationship between the fissure volume and mean coke size, which is standardized by the volume of the metal container. The correlations between the fissure volume and coke size before and after rotation were relatively low. This result suggests that the fissure volume is not a determining factor for the mean coke size, which contradicts the intuitive idea that smaller fissure volumes correspond to larger coke sizes. To explain this result, the formation of fissures in coke cakes was examined. Fig. 8a depicts a coke cake which has small particles (S0), whereas Fig. 8b shows a larger particle size one (S1). In Fig. 8b, which shows a larger mean coke size, wider fissures are apparent. Consequently, an increase in the fissure volume in the width direction did not seem to contribute to the division of the coke lump, suggesting that the effect on the coke size reduction was minimal. Therefore, the volume of coke fissures may not directly determine the mean coke size in coke cakes with a variety of fissure widths.

Figure 7

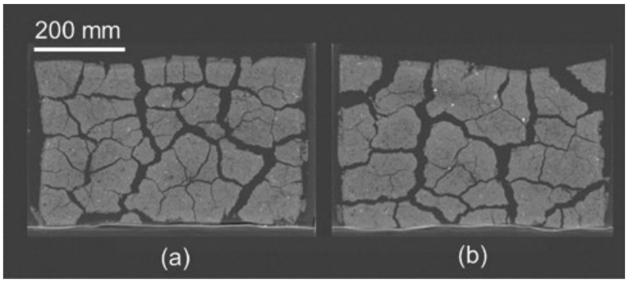
Relationship between fissure volume and size of coke; MS 0 rev/+25 mm (a) and MS 30 rev/+25 mm (b).



Relationship Between Fissure Plane Area and Coke Size: Fig. 9 illustrates the relationship between the fissure area and mean coke size. The area was standardized according to the size of the metal container to evaluate as fissure density. Irrespective of the rotational impact, the larger the fissure area, the smaller the mean coke size. This correlation was considerably stronger than that of the fissure volume. Therefore,

Figure 8

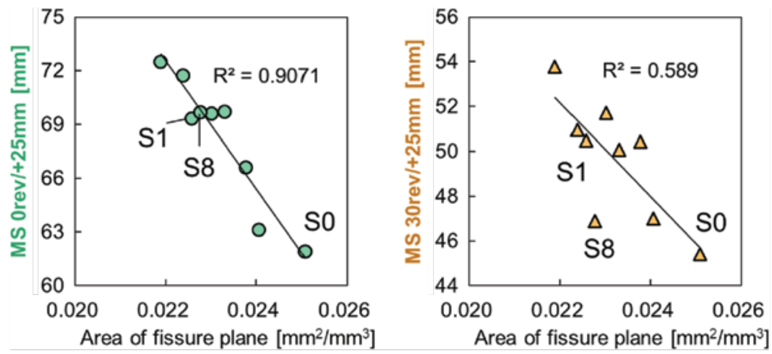
Compare slice of coke cake: Small mean size coke (S0: MS 0 rev/+25 mm = 61.9 mm) (a) and large size coke (S1: MS 0 rev/+25 mm = 69.3 mm) (b).



the fissure plane area is believed to be the dominant factor. This finding supports discussions regarding 2D slice images in past research that focus on fissure density. This high correlation validates consideration of the fissure plane that less fissure density corresponds to larger coke sizes. However, focusing on the coke mean size after rotation impact, the results show that the correlation between the fissure plane area and mean size is incomplete, especially for sample S8. This indicates that the fissure plane is not the sole factor influencing the coke particle size, suggesting the existence of other factors. Fig. 10 shows a slice image of sample S8, which demonstrates a large deviation from prediction line. The presence of numerous small cracks in S8 sample leads to the belief that the small cracks are crucial factors in estimating the coke size of after rotation.

Figure 9

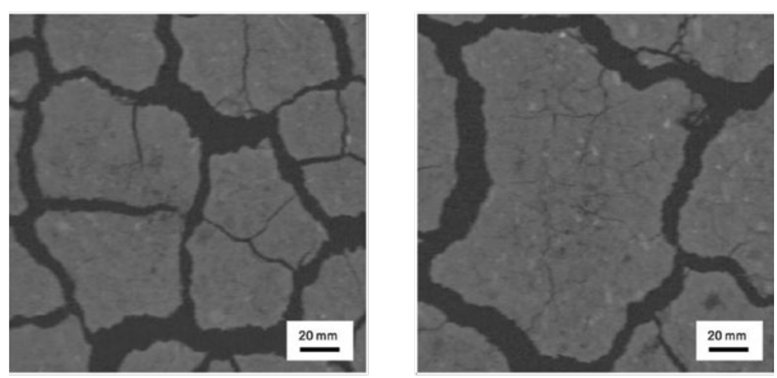
Relationship between area of fissure plane and coke mean size: MS 0 rev/+25 mm (a) and MS 30 rev/+25 mm (b).



(a) (b)

Figure 10

Comparison of X-ray CT images between levels with similar particle sizes before rotational impact but significantly different particle sizes after rotational impact: S1: MS 0 rev/+25 mm = 69.3 mm, MS 30 rev/+25 mm = 50.5 mm (a) and S8: MS 0 rev/+25 mm = 69.7 mm, MS 30 rev/+25 mm = 46.9 mm (b).



(a) (b)

Conclusions

Medical x-ray CT and three-dimensional image analysis to quantitatively evaluate the number and dimensions of coke fissures while ensuring representativeness, to estimate coke size. Consequently, the following insights were gained:

- A novel method was developed for extracting the fissure plane using three-dimensional image analysis. Using this method, the area of the fissure plane within the coke cake was quantitatively evaluated.
- A good correlation was shown between the area of the fissure plane and the coke mean size before rotation impact (MS 0 rev/+25 mm). It was confirmed that the area of the fissure plane governed the coke size in the absence of rotational impact, and the validity of the quantitative evaluation method for extracting the fissure plane was supported.
- The coke particle size after rotation impact (MS 30 rev/+25 mm) could not be predicted only from the area of the fissure plane, suggesting that the small fissures present within the lump are influential.

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