Effect of Iron Ore Reduction on Ferro-coke Strength with Hyper-coal Addition

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This study investigates the dominant factors affecting the strength of ferro-coke, which is produced by blending iron oxide with coal particles, with the addition of hyper-coal (HPC), to produce a high reactivity and strong coke. A diametral compression test for ferro-coke with and without HPC addition is performed. A three-dimensional ferro-coke model is then developed using micro X-ray computed tomography, and the relative proportions of pore, pore wall, iron, and pore space surrounding the iron particles, termed here “defect”, are quantified using this model. Moreover, a stress analysis is performed for the ferro-coke model. The diametral compression tests indicate that the strength of ferro-coke increases with the increasing blending ratio of HPC. The image-based modeling indicates that the wall thickness increases and stress concentration is relaxed with increasing addition of HPC due to enhancement of the adhesiveness of coal particles. On the other hand, the relative proportion of the “defect” is independent of HPC addition. Therefore, ferro-coke strength is found to be determined not by the “defect” around iron oxide but by the wall thickness.

KEY WORDS: ferro-coke; hyper-coal; coke strength; 3D analysis; microstructure; micro X-ray computed tomography.

1. Introduction

Coke acts as a reducing agent, spacer, and heat source, and its strength is important for stable operation of a blast furnace.1,2) In recent years, utilization of high-reactivity coke has been necessary to enhance the efficiency of blast furnace operations with effective use of carbon resources.3,4) High-reactivity coke has received substantial attention because its use has been reported to decrease the reducing agent rate, which is an index of the use of carbonaceous materials in steel making processes.5,6) Ferro-coke is one of the high-reactivity cokes, which is produced by blending iron ore with coal during coke production. The reactivity and strength of ferro-coke have been widely investigated. Nomura et al.7) reported that iron ore decreases the expansibility of coal particles even though ferro-coke has a high reactivity. Yamazaki et al. demonstrated that a decrease in the expansibility of coal particles reduces their adhesiveness.8) Yamamoto et al. produced different ferro-cokes with varying coal properties and blending ratios of coals and indicated that some of them show the same strength as chamber oven coke for the same conversion after reaction.9) In the above studies, reactivity and strength of ferro-coke after carbonization have been investigated; however, the effect of the reduction of iron ore during carbonization has not been discussed yet. Therefore, it is necessary to identify the dominant factors which determine the strength of ferro-coke and to understand its coking phenomena.

The use of hyper-coal (HPC) as a binder in coke production processes to enhance coke strength has been investigated. HPC begins to soften at low temperature, shows a high fluidity, and demonstrates the possibility of enhancing coke strength by blending with low-rank coals.10) Uchida et al.11) reported that iron oxide occupies the spaces between coal particles in ferro-coke and inhibits the adhesiveness of coal particles. However, these researchers also showed that blending HPC in ferro-coke enhances the adhesiveness of coal particles as well as coke strength and summarized that the adhesiveness of coal particles is one of the dominant factors in coke strength. Uchida et al. investigated the effect of HPC on the microstructural formation of ferro-coke and showed that HPC contributes to the adhesiveness of coal particles at the thermoplastic temperature, whereas HPC receives the influence of iron oxide.12) Therefore, the blending ratio of coal, HPC and ferro-coke is found to affect the microscopic structure and strength of coke. Changes in the microscopic structure include changes in the adhesiveness of coal particles owing to iron oxide at the thermoplastic temperature and decreases in the matrices of HPC and coal by the reduction of iron oxide above the
thermoplastic temperature. To investigate the microscopic structure of coke and its strength, Hiraki et al.\textsuperscript{13}) reproduced the three-dimensional (3D) microscopic structure of coke using cross-sectional images obtained by micro X-ray computed tomography (CT), performed stress analyses, and quantified the wall thickness of pores, which was proposed by Lindquist et al.\textsuperscript{14}) Consequently, they discovered a relationship between the wall thickness of pores in the three-dimensional microscopic structure and coke strength and demonstrated the advantage of investigating the adhesiveness of coal particles using the wall thickness of pores and coke strength. However, the relationships between both the wall thickness of pores and the presence of iron oxide particles on the microscopic structure of coke and coke strength have not yet been quantified.

In this study, the coke strength obtained from tensile stress tests is compared with that obtained from stress analyses based on the three-dimensional microscopic structure of ferro-coke provided by micro X-ray CT images. The investigation of the microscopic structure of ferro-coke is evaluated using the wall thickness of pores and the pore space surrounding iron particles, herein referred to as the “defect.” The wall thickness of pores in the three-dimensional microscopic structure determines the adhesiveness of coal particles and the “defect” represents the coke matrix that progressively diminishes in response to the reduction reaction of iron oxide in the coking process.

2. Experiment

2.1. Sample Preparation

The characteristics of the samples used in the experiments are listed in Tables 1–3. Donaldson, which is one of the slightly caking coals, is used as a sample wherein HPC is used as a binder and iron ore (MBR) is used as iron source. The thermoplastic temperature, maximum fluidity temperature, resolidification temperature, and maximum fluidity are indicated in Table 4. The particle sizes of the sample constituents are listed in Table 5, and the blending ratios of samples A–D are listed in Table 6. The coking condition employed is the same as that used previously.\textsuperscript{11}) The samples used for the diametral compression tests described below are 25 mm in diameter and 15 mm in thickness. Samples of 7 mm diameter are also prepared for investigation of the microstructure of ferro-coke, and samples of 3 mm diameter are used to study the pore structure around iron oxide particles.

### Table 4. Physical properties obtained by Gieseler plastometer for Donaldson coal and HPC.

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<tr>
<td>Donaldson coal</td>
<td>408</td>
<td>430–436</td>
<td>451</td>
<td>0.78</td>
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<tr>
<td>HPC</td>
<td>242</td>
<td>351–436</td>
<td>476</td>
<td>&gt;4.8</td>
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### Table 5. Average particle size of Donaldson coal, HPC, and MBR [mm].

<table>
<thead>
<tr>
<th></th>
<th>Donaldson coal</th>
<th>HPC</th>
<th>MBR</th>
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<tr>
<td>[mm]</td>
<td>&lt;1.0</td>
<td>&lt;0.15</td>
<td>&lt;0.25</td>
</tr>
</tbody>
</table>

### Table 6. Blending ratios of Donaldson coal, HPC, and MBR for samples A–D [%].

<table>
<thead>
<tr>
<th>Sample</th>
<th>Donaldson coal</th>
<th>HPC</th>
<th>MBR</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>70</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>65</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>C</td>
<td>60</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>55</td>
<td>15</td>
<td></td>
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### Table 3. Ultimate analysis for MBR [wt%].

<table>
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<tr>
<th></th>
<th>T–Fe</th>
<th>FeO</th>
<th>SiO₂</th>
<th>CaO</th>
<th>Al₂O₃</th>
<th>MgO</th>
<th>P</th>
<th>S</th>
<th>Na</th>
<th>K</th>
<th>TiO₂</th>
<th>Mn</th>
<th>Zn</th>
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<tr>
<td>[wt%]</td>
<td>67.5</td>
<td>0.21</td>
<td>1.31</td>
<td>0.01</td>
<td>0.73</td>
<td>0.01</td>
<td>0.033</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.07</td>
<td>0.11</td>
<td>0.003</td>
</tr>
</tbody>
</table>
In recent years, modeling based on digital images has been widely applied for reproducing composite materials with complicated shapes and for evaluating the growth of the cavernous tissue of biological bone. In this study, digital image modeling is used to construct a three-dimensional coke model for investigation of the microscopic structure of ferro-coke and for the construction of the analytical object for stress analysis.

X-ray CT (ScanXmate D160TS110, Comscantecno Co., Ltd.) is employed to reproduce the three-dimensional structure of the ferro-coke samples described above. X-ray CT measurements were conducted at an X-ray tube potential of 100 kV and a current of 100 μA. For the ferro-coke samples of diameters 7 mm and 3 mm, 140 and 250 X-ray CT images were taken at a resolution of 32 μm/pixel and 8 μm/pixel, respectively. X-ray CT images of samples A–D are shown in Figs. 1(a)–1(d), respectively. The gray segments of the images are coke matrices, the black segments are pores, and the white segments are ash components or iron particles. Ash components or iron particles appear white because X-rays are less transmissive in the ash components or iron particles than in the coke matrix.

The procedure used for constructing the three-dimensional ferro-coke model is illustrated in Fig. 2. The cross-sectional surface images are converted to the grayscale ones, and the binary images of the coke matrices or pores, ash components, and iron particles are produced using the grayscale histogram in the image-editing software (WinROOF Ver. 6.1.0, MITANI CORPORATION). The threshold of the X-ray CT images is subsequently set using the existence fraction of the coke matrices, pores, and iron particles. Finally, the three-dimensional ferro-coke structures of the 7 mm and 3 mm diameter samples are constructed as voxels by stacking the cross-sectional surface images and assuming pixel heights of 32 and 8 μm/pixel, respectively.

2.4. Evaluation of the Pore Wall Thickness in the Three-dimensional Structure

A schematic describing the algorithm used for evaluating the pore wall thickness is given in Fig. 3. In this study, the method proposed by Lindquist et al. is applied and the relationships between the results of the 3D analysis and the pore wall thickness are investigated. As shown in Fig. 3, a pore voxel is defined as number 0, whereas a coke matrix voxel adjacent to a pore voxel is defined as number 1, the coke matrix voxel next to number 1 is defined as number 2, and the numbering is repeated. The procedure is carried out from each pore boundary. The larger number indicates a location where the pore wall is thick because the location is far from the pore. The pore wall thicknesses of the coke matrices are evaluated by calculating the frequency distribution using the above method.

2.5. Quantitative Evaluation of the “Defect” around Iron Particles

The pores around iron particles in the microscopic structure of the ferro-coke after carbonization, which is described in Section 2.6, are evaluated. For example, in the cross-sectional surface of the microscopic structure derived from the 3D image constructed from CT images (resolution of 8 μm/pixel) of sample A, the gap between the iron particle and coke matrix is defined as a “defect”, which is marked with a black square in Fig. 4. The extraction process is also described in Fig. 4. The image processing is first performed as shown in Fig. 2, and the coke matrices, iron particles, and pores are classified (Fig. 4(a)). To evaluate the pore spaces surrounding the iron particles, the “defects” are first labeled as “defect candidates.” As shown in Fig. 4(b), the pores adjacent to the iron particle are marked as “defect candidate” number 1, whereas those pores adjacent to the “defect candidates” marked number 1 are marked as...
“defect candidate” number 2, and the procedure is repeated five times. However, almost all the pores are recognized as “defects” by this process and the extent of the “defects” is thereby overestimated. Therefore, it is necessary to distinguish between “defects” and pores from the selected “defect candidates” to extract the actual “defect.” The brightness value distribution is obtained by the image processing of Fig. 4, and the coke matrix, iron particles, and pores are distinguished by setting the appropriate threshold. It is thereby possible to distinguish the normal pores from the incomplete pores (“defect”). Hence, by subtracting Fig. 4(c) from Fig. 4(b), the “defect” can be extracted as shown in Fig. 4(d).

2.6. Numerical Analysis Using the Finite Element Method (FEM)

To investigate the effect of the microscopic structure of ferro-coke on the stress concentration, 3D stress analyses are performed for samples A–D listed in Table 6 using the FEM. The general size of the “defects” in the microscopic structure of ferro-coke defined in the previous section is on the order of micrometers, and it is necessary to resolve the fine microstructure to investigate the effect of HPC addition on “defect.” To this end, a finite element mesh based on voxels representative of volumes 32 μm³ or 8 μm³ is applied to the analytical objects represented by Fig. 2(d) for numerical analysis.

The governing equations for microscopic elastic displacement are given by Eqs. (1)–(3) as follows.

\[
\sigma_{ij} = \frac{F}{A} \quad \text{(1)}
\]

\[
\sigma_{ij} = E_{ijkl} \varepsilon_{kl} \quad \text{(2)}
\]

\[
\varepsilon_{ij} = \frac{1}{2} (u_{ij} + u_{ji}) \quad \text{(3)}
\]

In this study, the governing equations are discretized by the FEM. The calculations employ the eight-node isoparametric mesh element. The calculations are performed using parallel computation, and the displacement of each node is calculated by the conjugate gradient (CG) method using element by element operations.

Stress analysis assuming uniaxial tension is performed for an analytical object illustrated in Fig. 2(d). For boundary conditions, the constraint condition is given at the lower nodes in the computational domain and the summation of the reaction force caused by the enforced displacement for a unit area is prescribed at the upper nodes in the tensile direction. In the calculation, the coke matrix is assumed to consist of active components with an elastic coefficient of 24 GPa and a Poisson ratio of 0.3 derived from the measurement results of the nanoindentation method. The elastic coefficient of pores is assumed to be smaller than that of the coke matrix by a factor of 10⁻⁴. The metallic iron is treated as a pore because it does not disperse the stress that arises in the microscopic structure. Though the assumed material constants are prescribed for pores, it was confirmed that the calculated results both with and without application of mesh to pores are in excellent agreement. The calculated results are evaluated by the maximum principal stress used for brittle materials because coke is known to show brittle fracture. Here, the principal stress indicates the normal stress in the coordinate where the shear stress is zero.

3. Results and Discussion

3.1. Changes in Coke Strength with the Addition of HPC

The Weibull plots for samples A–D, which are calculated from the measurements of the diametral compression

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Fig. 3. Schematic of the algorithm for evaluating the pore wall thickness. (Online version in color.)

Fig. 4. Schematic of the algorithm for extracting the “defect”.

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test, are shown in Fig. 5, and the scale parameters of the Weibull plots are given in Fig. 6. The scale parameters are observed to increase with the addition of HPC, which indicates that the strength of ferro-coke increases with the addition of HPC. This is because the addition of HPC contributes to the adhesiveness of coal particles as discussed previously.\(^{11}\) Therefore, the addition of HPC changes the microscopic structure of ferro-coke and the stress distribution in the ferro-coke matrix also changes. Therefore, the 3D microscopic structure of ferro-coke is reproduced by the CT images and analysis of the pore wall thickness and the extraction of the “defect.” The effect of changes in the microscopic structure of ferro-coke with the addition of HPC on the stress analysis computation is discussed, and the dominant factors of the strength of ferro-coke are investigated.

### 3.2. Evaluation of the Pore Wall Thickness in the Three-dimensional Microscopic Structure

To quantitatively evaluate the micrometer scale change in the pore wall thickness with the addition of HPC, the pore wall thicknesses of the microscopic structures in samples A–D are measured. Quantitative descriptions of the 3D microscopic structures of samples A–D are listed in Table 7, and cross-sectional surfaces of samples A and D are shown in Fig. 7. Because the resolution of the computational domain is 32 \(\mu\)m, it is not possible to evaluate the coke matrix on a scale less than 32 \(\mu\)m. As qualitatively described in Fig. 7, the pore walls are generally thicker for sample D than for sample A. The pore wall thicknesses in the 3D microscopic structures of samples A–D are indicated in Fig. 8. Note that the pore wall thickness in the horizontal axis corresponds with the numbers in Fig. 3. A larger number shown on the abscissa indicates that the pore wall exists inside the coke matrix and the matrix is thick. The addition of HPC decreases pores and the existence fraction for wall numbers 1–4 progressively increases with increasing HPC addition except for sample D; therefore, the addition of HPC is found to thicken the pore walls in ferro-coke. The microscopic structure is formed by responding to the effect of iron oxide in the carbonization process. Nomura et al.\(^{7}\) reported that the decomposition of the softened components caused by the addition of iron oxide decreases the expansi-

![Fig. 5. Weibull plots for samples A–D.](image)

![Fig. 6. The scale parameters of the Weibull plots given in Fig. 5 for the blending ratios of HPC.](image)

![Fig. 7. Cross-sectional images of the ferro-coke model, including the pore, matrix, and iron, for samples A and D. (Online version in color.)](image)

![Fig. 8. Existence ratios of the pore and matrix (each wall thickness number) for samples A–D.](image)

Table 7. Existence ratios of pore, matrix, iron, and “defect” in the ferro-coke model for samples A–D [%].

<table>
<thead>
<tr>
<th>Sample</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
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<tbody>
<tr>
<td>Pore</td>
<td>67.2</td>
<td>67.4</td>
<td>61.6</td>
<td>65.7</td>
</tr>
<tr>
<td>Matrix</td>
<td>28.9</td>
<td>28.9</td>
<td>35.3</td>
<td>31.4</td>
</tr>
<tr>
<td>Iron</td>
<td>3.9</td>
<td>3.7</td>
<td>3.1</td>
<td>2.9</td>
</tr>
<tr>
<td>Defect</td>
<td>2.0</td>
<td>2.0</td>
<td>1.7</td>
<td>1.6</td>
</tr>
</tbody>
</table>
bility of coal particles. Uchida et al.\textsuperscript{12} reported that the softened components of HPC being decomposed by iron oxide enhances the adhesiveness of coal particles. The addition of HPC inhibits the decomposition of the softened components of coal particles and the expansibility of coal particles does not substantially decrease. Consequently, the adhesiveness of coal particles is enhanced and the pore wall thickness increases. In sample A, the softened components of coal particles are decomposed by iron oxide at the thermoplastic temperature and the expansibility of coal particles appears to decrease. In sample D, on the other hand, the softened components of HPC inhibits the decomposition of the softened components of coal particles by iron oxide and the expansibility of coal particles appears to increase, whereas the adhesiveness of coal particles is enhanced. This effect does not appear in the pore wall thickness with the present resolution and the pore wall thickness with higher resolution or another parameter which can evaluate the adhesiveness would enable to predict an increase in coke strength for the large amount of HPC addition.

3.3. Change in the Microscopic Structure around the Iron Particle (the “Defect”)

As shown in Fig. 7 and discussed in the above section, small pores form around iron particles, which are called “defects” in this study. Because pores are generated around the iron particles, the reduction reaction of iron oxide is thought to progress by consuming the coke matrix. To investigate the “defect” generated by the reduction reaction of iron oxide around the iron particle above the resolidification temperature, the “defect” is extracted.

The images of the microscopic structure of the ferro-coke sample of 3 mm diameter taken with a resolution of 8 μm/pixel, which is reproduced at a size of 2.0 mm × 2.0 mm × 2.0 mm, is investigated. The classified results of the coke matrix, pore, iron particle, and “defect” in samples A–D are indicated in Fig. 9, and quantitative descriptions of the cross-sectional surface of the 3D microscopic structure of ferro-coke are listed in Table 7. No remarkable differences are observable; however, the existence fraction of the “defect” slightly decreases with increasing HPC addition. Uchida et al.\textsuperscript{12} reported that iron oxide exists as magnetite (Fe₃O₄) independent of the blending ratio of HPC addition. The microscopic structure of ferro-coke was observed, the pore wall thicknesses and the “defects” were extracted, and the effect of the blending ratio of HPC on these was investigated in the above sections. The effect of the extracted “defect” on coke strength is investigated, and the dominant factor in coke strength is discussed. The average values of the maximum principal stress obtained by the 3D stress analyses are shown in Fig. 10. Among these, pore and matrix components smaller than 32 μm cannot be evaluated because the image resolution is 32 μm/pixel. The different computational domains of the three parts from the CT images are computed for each sample condition. As a result, the addition of HPC decreases the maximum principal stress, and no remarkable differences in the values of the average maximum principal stress are observed for samples B–D. From the above result, it is clear that the addition of HPC enhances the adhesiveness of coal particles. However, the effects of an increasing HPC addition cannot be confirmed because the effects of matrices and “defects” on a scale less than 32 μm, which changes with increasing HPC addition, is not reflected in the average value of the maximum principal stress. In the following section, not the average value of the maximum principal stress but the maximum principal stress itself will be discussed.

![Fig. 9](image_url)

**Fig. 9.** Cross-sectional images of the ferro-coke model, including the pore, matrix, iron, and “defect”, for samples A and D. (Online version in color.)

![Fig. 10](image_url)

**Fig. 10.** Average maximum principal stress in the ferro-coke model for each blending ratio of HPC.
3.5. The Relationship between the Microscopic Structure and Stress Concentration

In the above results, the dominant factor of coke strength was found to be the pore wall thickness, which increases with an increasing adhesiveness of coal particles. However, the average values of the maximum principal stress were discussed, and it is necessary to investigate the relationship between the pore wall thickness and the inherent stress in the microscopic structure to understand the relationship between the change in the microscopic structure and the stress therein. The stress distribution of sample D obtained by the 3D stress analysis is shown in Fig. 11, and fraction of the maximum principal stress determined for samples A–D are indicated in Fig. 12. Hiraki et al.\textsuperscript{13} reported that the 3D wall thickness increases with increasing coke strength, and the proportion of the matrix that exhibits a maximum principal stress of more than 5 MPa decreases. Focusing on the matrix regions that exhibit a maximum principal stress of more than 5 MPa in the horizontal axis, the existence fraction of the matrix with a maximum principal stress over 5 MPa in samples B–D containing HPC decreases compared with that of sample A without HPC. Additionally, the maximum principal stress seems to decrease with an increase in the amount of HPC addition while this trend does not appear with the mean values of the maximum principal stress as shown in Fig. 10. This is because the addition of HPC enhances the adhesiveness of coal particles, and the inherent stress in the microscopic structure in ferro-coke is thereby absorbed. Therefore, the maximum principal stress distribution in the microscopic structure of ferro-coke would change with an increase in the pore wall thickness, which is caused by the enhancement of the adhesiveness of coal particles. This fact suggests strength of coke should increase with a decrease in the maximum principal stress since the part with the maximum principal stress should be the origin of fracture.

To investigate the stress distribution in the microscopic structure of ferro-coke in detail, the stress concentration and the pore wall thickness are compared. The maximum principal stress distributions shown in Fig. 12 are again shown in Fig. 13 for each pore wall thickness represented by the numbers 1, respectively. Here, the dominant factor of coke strength is the pore wall thickness in the microscopic structure formed by the adhesiveness of coal particles. In Fig. 10, the addition of HPC is found to join the coke matrices and absorb the stress inherent in the coke microscopic structure because of the enhancement of the adhesiveness of coal particles. In addition, the region of the coke matrix in which the stress is greater than 5 MPa in thick pore walls appears to affect ferro-coke fracture. For a wall thickness of 1, as shown in Fig. 13, the existence fraction of the matrix with a stress greater than 5 MPa decreases for samples B–D with HPC compared with sample A without HPC. These results indicate that the addition of HPC absorbs the stress in the microscopic structure and the stress concentration decreases because the addition of HPC enhances the adhesiveness of coal particles and thickens the pore walls. On the other hand, no remarkable differences are seen to depend on the “defects” generated in the sample with or without the addition of HPC, as is shown in Table 7 and discussed in Section 3.3. Therefore, coke strength appears to depend on the pore wall thickness rather than the “defects” induced by the iron particles. Above all, the enhancement of the adhesiveness of coal particles by HPC addition disperses the stress in the microscopic structure of ferro-coke and absorbs the stress concentrated in thick pore walls, such that matrix fracture might be controlled.

4. Conclusion

In this study, the pore wall thickness in the 3D micro-
scopic structure of ferro-coke is evaluated. The combination of HPC and coal with unreacted iron particles above the resolidification temperature is investigated by extracting the coke matrices and iron particles in ferro-coke and evaluating the pores surrounding the iron particles quantitatively. Moreover, the relationship between the 3D microscopic structure of ferro-coke and the stress distribution therein is investigated by stress analyses using finite element analysis based on the digital images. This study can be summarized as follows.

- The addition of HPC to coal thickens the pore walls of ferro-coke, inhibits the tendency of iron oxide to decrease the expansibility of coal particles, and enhances the adhesiveness of coal particles. Consequently, the stress in the microscopic structure of the ferro-coke is absorbed and coke strength is enhanced.

- A large difference with and without the addition of HPC does not appear in the pores surrounding the iron particles generated by the reduction reaction of iron oxide. Hematite appears to be reduced to magnetite at the thermoplastic temperature. Coke strength is influenced by the pore wall thickness rather than by the pores surrounding the iron particles generated by the consumption of the coke matrix during the reduction reaction of iron oxide. Therefore, it is necessary to enhance the adhesiveness of coal particles at the thermoplastic temperature for strong coke production.

Acknowledgement

We would like to express our sincere appreciation to the authors of “Elucidation of the Mechanism for Developing Strength of New Binders” for their permission to use some of the results found therein. This study conducted on consignment from Kobe Steel, Ltd. as a part of the “Project to Develop Technology for an Innovative Iron-making Process for Efficient Use of Resources,” which was funded by the New Energy and Industrial Technology Development Organization (NEDO).

Nomenclature

<table>
<thead>
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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$E$</td>
<td>elastic modulus [N/m²]</td>
</tr>
<tr>
<td>$F$</td>
<td>body force [N/m²]</td>
</tr>
<tr>
<td>$u$</td>
<td>displacement [-]</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>strain [-]</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>stress [N/m²]</td>
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Greek symbols

REFERENCES