Development of Ferro-Coke Process for Mitigating CO2 Emissions in Ironmaking

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(Project Leader)

JFE Steel Corp.
Nippon Steel & Sumitomo Metal Corp.
Kobe Steel, Ltd.
**Concept of Innovative ironmaking process**

**CO₂ mitigation and usage of low grade resources in ironmaking process**

**Conventional ironmaking process**
- Ore fine
- Coking coal
- High grade
- Sintering machine
- Sinter
- Burden 1
- Coke
- Coke ovens
- Burden 2

**Innovative Ironmaking process**
- Ore fine
- Low grade
- Innovative binder
- Forming
- Shaft furnace
- Ferro-coke
- Burden 3

**Energy savings**
- Partial replace
- (CO₂ mitigation)

**Utilization of low grade ore/coal**

**NEDO/METI grant project**
- Period: FY2009/10, FY2011/12
- Grant ratio: 1/2
- Participants: JFE Steel, Nippon Steel, Sumitomo Metals, Kobe Steel, Major Japanese Universities
Development of innovative ironmaking process

Three key technologies

- Structure and compositions of agglomerates
- Carbonization and reduction
- Blast furnace operation using Ferro-coke

Three key technologies

- Low grade Ore and coke
- Innovative binder
- Briquette

- Direct heating
- Carbon particle
- Binder
- Ore particle

Blast furnace (Coke mixed charging)

Ferro-coke Sintered ore layer

Coke layer

Metallic iron Carbon(coke)

Ferro-coke
# Properties of coal and ore

## Coal Properties

<table>
<thead>
<tr>
<th>Coal</th>
<th>Ro(%)</th>
<th>VM(%)</th>
<th>MF(ddpm)</th>
<th>Ash(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.72</td>
<td>36.1</td>
<td>307</td>
<td>8.4</td>
</tr>
<tr>
<td>B</td>
<td>1.80</td>
<td>11.2</td>
<td>0</td>
<td>8.6</td>
</tr>
</tbody>
</table>

Coal A: Slightly caking coal  
Coal B: Non caking coal

## Ore Properties

<table>
<thead>
<tr>
<th></th>
<th>T.Fe</th>
<th>FeO</th>
<th>CaO</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>MgO</th>
<th>P</th>
<th>S</th>
<th>Na</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>67.5</td>
<td>0.21</td>
<td>0.01</td>
<td>0.49</td>
<td>0.73</td>
<td>0.01</td>
<td>0.033</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>
Hot briquetting test in bench plant

Briquette machine

<table>
<thead>
<tr>
<th>Briquette conditions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total roll power</td>
<td>30〜50ton</td>
</tr>
<tr>
<td>Briquetting pressure</td>
<td>3〜5 t/cm</td>
</tr>
<tr>
<td>Roll diameter</td>
<td>650mm</td>
</tr>
<tr>
<td>Roll speed</td>
<td>6 rpm</td>
</tr>
<tr>
<td>Briquetting temp.</td>
<td>100〜120℃</td>
</tr>
<tr>
<td>Cup volume</td>
<td>6cc</td>
</tr>
<tr>
<td>Coal/ore (mass%)</td>
<td>Coal/ore = 7/3</td>
</tr>
<tr>
<td>Binder (mass%)</td>
<td>SOP+ASP=5-9%</td>
</tr>
<tr>
<td>Particle size</td>
<td>Coal: -3mm, Ore A: -250 μm B: -1mm</td>
</tr>
<tr>
<td>Total sample weight</td>
<td>20kg-dry/batch</td>
</tr>
</tbody>
</table>

Size: 30x25x15mm
Carbonization tests in batch furnace

Carbonization test conditions
Carbonization temp (at wall) : 1000℃
Carbonization time : 6h
Packing : with/without coke breeze

Schematics of carbonization furnace

Carbonization temp at center (°C)

Time (min)

Carbonization temperature

Without coke fine
Embedded to coke fine

Packing conditions

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**Effect of coal and ore ratio on adhesion and swelling**

<table>
<thead>
<tr>
<th>Coal : A/B = 70/30 (mass%)</th>
<th>Ore; 0mass%</th>
<th>Ore; 10mass%</th>
<th>Ore; 30mass%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coal A 100%</strong></td>
<td><img src="image1.jpg" alt="Image" /></td>
<td><img src="image2.jpg" alt="Image" /></td>
<td><img src="image3.jpg" alt="Image" /></td>
</tr>
<tr>
<td><strong>Coal A 70% + Coal B 30%</strong></td>
<td><img src="image4.jpg" alt="Image" /></td>
<td><img src="image5.jpg" alt="Image" /></td>
<td><img src="image6.jpg" alt="Image" /></td>
</tr>
</tbody>
</table>

Adhesion ratio of the ferro-coke at the blending ratio of 30% and 70%
Development of an innovative binder for Ferro-coke

Objectives
To develop an innovative binder for Ferro-coke by utilizing the KSL’s proprietary coal solvent extraction technology (Hyper-coal)

Targets
Higher Ferro-coke strength compared to a conventional asphalt pitch binder (ASP)

Features of the innovative binder process
1. No hydrogenation, mild reaction conditions (ca. 400°C, 2MPa)
2. Product separation by gravity settling
3. Recycled use of naphthalene-based solvent

<table>
<thead>
<tr>
<th>Slurry make up</th>
<th>Extraction</th>
<th>Solid-Liquid separation</th>
<th>Solvent recovery</th>
</tr>
</thead>
</table>

Photo Test production facility for the innovative binder
Capacity: 0.1 ton-coal/day
**Effects of the extraction conditions on the binder properties**

- Softening temperature of the binder can be controlled by the extraction conditions.
- The innovative binder prepared by extracting a bituminous coal at 410 °C exhibited lower softening temperature and superior fluidity than the ASP binder.

⇒ The enhanced fluidity of the binder may improve the inter-particle adhesion between ore and coal particles under the Ferro-coke carbonization conditions.

![Graph showing the effects of extraction conditions on binder properties](image-url)
Experiments for evaluating the innovative binders

Table Compositions for the feed

<table>
<thead>
<tr>
<th>No.</th>
<th>Coal A</th>
<th>Coal B</th>
<th>Ore A</th>
<th>ASP</th>
<th>HPC1</th>
<th>HPC2</th>
<th>SOP</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26.6</td>
<td>39.9</td>
<td>28.5</td>
<td>2.0</td>
<td>3.0</td>
<td></td>
<td></td>
<td>Ref.</td>
</tr>
<tr>
<td>2</td>
<td>26.6</td>
<td>39.9</td>
<td>28.5</td>
<td>1.0</td>
<td>1.0</td>
<td>3.0</td>
<td></td>
<td>ASP/HPC: 1</td>
</tr>
<tr>
<td>3</td>
<td>26.6</td>
<td>39.9</td>
<td>28.5</td>
<td>1.0</td>
<td>1.0</td>
<td>3.0</td>
<td></td>
<td>ASP/HPC: 1</td>
</tr>
<tr>
<td>4</td>
<td>26.6</td>
<td>39.9</td>
<td>28.5</td>
<td>2.0</td>
<td>3.0</td>
<td></td>
<td></td>
<td>HPC: 2</td>
</tr>
<tr>
<td>5</td>
<td>26.6</td>
<td>39.9</td>
<td>28.5</td>
<td>2.0</td>
<td>3.0</td>
<td></td>
<td></td>
<td>HPC: 2</td>
</tr>
</tbody>
</table>

Extraction temperature for the innovative binders: HPC1, 380°C; HPC2, 410°C

Table Briquetting conditions

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>3-5 ton/cm</td>
</tr>
<tr>
<td>Roll diameter</td>
<td>650 mm</td>
</tr>
<tr>
<td>Rotation speed</td>
<td>6 rpm</td>
</tr>
<tr>
<td>Material temperature</td>
<td>170 °C</td>
</tr>
<tr>
<td>Pocket volume</td>
<td>6 cc (30x25x15 mm)</td>
</tr>
<tr>
<td>Coal/ore ratio</td>
<td>7/3 (by weight)</td>
</tr>
<tr>
<td>Binder content</td>
<td>SOP, 3%; ASP (or HPC), 2%</td>
</tr>
<tr>
<td>Particle size</td>
<td>Coal, &lt;2mm; Ore, &lt;250µm</td>
</tr>
<tr>
<td>Feed rate</td>
<td>20 kg/batch</td>
</tr>
</tbody>
</table>
It was demonstrated that the innovative binder prepared by solvent extraction of coal at 410°C improves the Ferro-coke strength compared to the ASP binder.
Effect of coking temperature and holding time

Effect of coking temperature on the reduction ratio

Bench scale plant of 0.5 t/d and products.
DEM model development of Ferro-coke plant

Discrete Element Method

Inter particle

Voigt model

Width: 1.25m
Length: 1.33m
Height: 14.0m
3D images of tracer particle flow

Initial charging
Process flow of a pilot plant of 30t/d

Iron ore 30%
Non-coking coke 70%
Crusher

Dryer Pre-heater
Mixer/kneader
Shaft furnace
Gas coolers
Gas heating
Carbonization/Reduction
Plant
Sintered ore
Oven coke

Furnace type: Shaft
Capacity: 30t/d
Location: JFE Steel Corp., East Work (Keihin)

Blast furnace
Briquette
Ferro-coke
Overview of the 30t/d ferro-coke pilot plant

- Briquetting
- Carbonization
- Crushing and heating
- Gas recycle
- Stock yard
Typical continuous briquetting operation

- Continuous operation for 5hr
- Start briquetting
- Charging start

Temperature of mixer [°C]

- Target range of BQ force

BQ force [t]

- Target DI > 88

Strength ID30/16 [-]

Time

Briquette for carbonization tests

10mm

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Development of innovative ironmaking process

Three key technologies

- Structure and compositions of agglomerates
- Carbonization and reduction
- Blast furnace operation using Ferro-coke

Innovative binder

Low grade Ore and coke

Briquette

Coal particle

Binder

Ore particle

Direct heating

Ferro-coke

Sintered ore layer

Coke layer

Blast furnace (Coke mixed charging)

Metallic iron

Carbon(coke)

Ferro-coke
Basic concept of low carbon technologies

- RAR reduction in short term
  - Improve sinter reducibility
  - Burden distribution control
- Thermal reserve temp. Tw
  - Highly reactive coke
  - Carbon contained agglomerates
- Innovative agglomerates
- Catalytic effect for high reactivity

Pre-reduction

RAR reduction

Tw control

Catalytic effect

W point at 800°C

W point at 1000°C

O/Fe

Temp

CO₂/(CO+CO₂)

FeO

Fe

Highly reactive composite for Tw decrease
Experimental conditions with BIS and large thickness

- 30% of conventional coke was replaced with Ferro-coke.
- Different mixing conditions with Ferro-coke were tested.
- Condition with large layer thickness as plant, 330 mm, was tested.

**Diagram:**
- Blast furnace Inner reaction simulator
- Gas flow
- Solid flow
- Sinter
- Coke
- Ferro-coke
- Reducing gas
- 70mm
- 330mm
- 65mm

**Conditions:**
- Base: homogeneously mixed
- Upper layer: mixed in coke
- Coke layer: 330mm
- Sinter layer: 330mm
- Ferro-coke layer: 65mm
BIS tests
Temperature of thermal reserve zone was lowered by 100°C with using Ferro-coke.
Proper arrangement of Ferro-coke was homogeneously mixed or segregated in upper layer.

Both reactivity of sinter and Ferro-coke were large in homogeneously mixed.
Concept of Mathematical Blast Furnace Model

This mathematical blast furnace model can estimate inner furnace reactions when Ferro-coke is charged into blast furnaces.

Gasification model of Ferro-coke is required to evaluate the effect of Ferro-coke on blast furnace operation.
Measurement of gasification rate of Ferro-coke

An example of fractional gasification curve.

\[ k' = k \left( p_{CO_2} - \frac{p_{CO}}{K} \right) \]

\[ K = \exp\left( -\frac{170.790 - 174.56T}{RT} \right) \]
Modeling of gasification rate of Ferro-coke

Gasification model of Ferro-coke was combined into the mathematical blast furnace model.

\[ \text{Rate}_n = k_a \left( C_{CO_2}^b - C_{CO_2}^e \right) \cdot \epsilon_s \]

Where,
\[ \frac{1}{k_a} = \frac{1}{E_f \cdot k} + \frac{d_p}{6k_f} \]

Effective reaction rate constant

Gasification model of Ferro-coke made by Kyushu University was combined into the mathematical blast furnace model developed by NSSMC. The effect of Ferro-coke on blast furnace operation can be evaluated by the model.
Effect of Ferro-coke on temperature distribution, 
gas concentration in blast furnace

Variation of inner-furnace state due to the charge of Ferro-coke was estimated.
Stock yard of Ferro-coke for blast furnace test
Ferro-coke of 2100 ton was transported by truck to the direct charge bin.

Five days charging test was carried out in March 2013.
Concluding Remarks

The innovative inromaking process development was the final year of four years project in FY2012.

1) Optimization of production conditions of an innovative binder from Hyper coal process and evaluation at the pilot plant.
2) Successive operation of briquetting and carbonization was carried in the end of FY2011 and continuous production trials and charging tests to a blast furnace has successfully completed in FY 2012 to find process feasibility of the production process and technical subjects of blast furnace charging.
3) Development of charging condition for the optimum layer structure has been established at laboratory scale experiments.
4) Evaluation of blast furnace operation with the Ferro-coke at No.6 blast furnace in Chiba Works.